05 Evolution and biodiversity

Lemurs arrived on the Comoro Islands and Madagascar about 6.5 million years ago and have adapted to the many habitats available there. They used to be common on mainland Africa but natural selection, notably competition with other primates, has eliminated them from the continent.

Essential ideas

5.1	There is overwhelming evidence for the evolution of life on Earth.
5.2	The diversity of life has evolved and continues to evolve by natural selection.
5.3	Species are named and classified using an internationally agreed system.
5.4	The ancestry of groups of species can be deduced by comparing their base or amino acid sequences.

There are almost 2 million species on Earth that have been catalogued and given a scientific name, the biggest number being insects. However, there are many more species as yet unidentified, and it is impossible to know exactly how many there are in the biosphere: 5 million? 10 million? 20 million? Even more overwhelming is trying to imagine how many species there were in the past that have now gone extinct. The organisms on Earth today represent much less than 1% of all life forms that have ever existed. How life has changed over time and how we make sense of the living world around us is the focus of this chapter. Understanding the mechanisms by which species evolve by natural selection is arguably one of the most important and influential concepts in biology. So much can be explained by natural selection, from why zebras have stripes, to why new bacterial populations that are resistant to antibiotics are being found in hospitals.

5.1 Evidence for evolution

NATURE OF SCIENCE

Looking for patterns, trends, and discrepancies: there are common features in the bone structure of vertebrate limbs despite their varied use.

Understandings:

- Evolution occurs when heritable characteristics of a species change.
- The fossil record provides evidence for evolution.
- Selective breeding of domesticated animals shows that artificial selection can cause evolution.
- Evolution of homologous structures by adaptive radiation explains similarities in structure when there are differences in function.
- Populations of a species can gradually diverge into separate species by evolution.
- Continuous variation across the geographical range of related populations matches the concept of gradual divergence.

Applications and skills:

- Application: Development of melanistic insects in polluted areas.
- Application: Comparison of the pentadactyl limb of mammals, birds, amphibians, and reptiles with different methods of locomotion.

Charles Darwin (1809–82).

Darwin and Wallace

At the age of 22, Charles Darwin had the opportunity to travel on board the HMS *Beagle* for a scientific exploration mission starting in 1831 and lasting for 5 years. Little did he know that it would allow him to see nature in a new way and come up with what would become one of the most important, controversial, and misinterpreted ideas in biology: evolution by natural selection.

Darwin was not the only person to develop a theory to explain evolution. Darwin was surprised to discover in 1858 that Alfred Russel Wallace had independently developed a nearly identical theory. The two men presented their ideas jointly to the Linnaean Society in 1858.

What is evolution?

Evolution is defined as the process of cumulative change in the heritable characteristics of a population. The word heritable means that the changes must be passed on genetically from one generation to the next, which implies that evolution does not happen overnight. The word cumulative is in the definition to stress the fact that one change is usually not enough to have a major impact on a species. Finally, the word population is in the definition because the changes do not affect just one individual.

Over time, if enough changes occur in a population, a new species can arise in a process called speciation. The members of the new population will be different enough from the pre-existing population that they came from that they will no longer be able to interbreed. Such a process is rarely observable during a human lifetime. However, once you begin to understand evolution, it should become clear that all of life on Earth is unified by its common origins.

It has been argued that once evolution by natural selection is understood, many of the mysteries of nature are revealed. Although there are others, we will examine three phenomena that provide evidence for evolution by natural selection: the fossil record, animal breeding and homologous structures. Later, we will also look at DNA evidence. When the role of DNA in inheritance (genetics) became understood, it appeared to some to contradict evolution by natural selection; such contradictions often arise with new developments in science. In fact, DNA evidence provides new support for natural selection beyond anything Darwin could have dreamt of, and is referred to as the modern synthesis or neo-Darwinism, a combination of Darwin's ideas with a newer one, the idea of genetics that Mendel started, that was only confirmed long after both men had died.

Fossil hunting is the job of palaeontologists, and the best palaeontologists are willing to travel around the globe searching for bones, footprints, and plant remains. Some countries have policies controlling fossils to make sure that scientifically significant fossils are kept in museums or university collections. Other countries do not have such policies (or the policies are ignored by smugglers), and fossil hunters can sell fossils for profit to people wanting to add them to their personal collections. Should fossils be protected and conserved, or should they be considered as a commodity that can be bought and sold? What international organization should decide on and enforce such policies?

The fossil record and evolution

It is impossible to travel back in time, and the best clues scientists have about what life was like thousands or millions of years ago come from fossils. Fossils are the petrified remains or traces of animals and plants, and the fossil record is the accumulation of evidence from these remains and traces, such as skeletons and footprints. Palaeontologists have been collecting and classifying fossils in an organized fashion for almost two centuries.

The Museum of Comparative Anatomy in Paris, France.

If you have ever been to a museum full of fossils classified by their age, you may have noticed a few things that palaeontologists have discovered that provide convincing evidence for Earth's evolutionary past.

- Overall, the life that existed more than 500 million years ago was vastly different in appearance from life today.
- Although planet Earth has had extensive oceans for most of its existence, fish fossils have only been found in rocks 500 million years old or younger (less than 15% of the 3.5 billion year existence of life on our planet).
- Although most of the top predators today are mammals such as bears, orcas, big cats, and wolves, none of them existed at the time of the dinosaurs or before.
- Apart from organisms such as certain types of sharks, cockroaches, and ferns, the majority of living organisms today have no similar form in the fossil record.

One conclusion that can be drawn from studying fossils is that life on Earth is constantly changing. However, most of the changes have occurred over huge timescales (hundreds of thousands or millions of years); timescales that humans find difficult to grasp.

Ageing fossils

The age of a rock can be determined by carefully examining differences in the ratios of isotopes. Isotopes are versions of atoms that are heavier or lighter than other versions of the same atom (carbon-14 has more mass than carbon-12). If a fossil of a bone or shell has a high level of carbon-14, for example, it is younger than a bone or shell that has a very low level of carbon-14. This is because carbon-14, also written ^{14}C, is

radioactive but slowly loses its radioactivity; as it gives off its radioactivity, it changes its identity into another atom, nitrogen-14. This process of a radioactive parent isotope changing into a stable daughter isotope is called decay. The speed at which this happens is expressed as an isotope's half-life. Half-life is defined as the time it takes for half of the parent isotope to decay into a stable daughter isotope.

The half-life of ^{14}C is 5730 years, meaning that, when an animal dies, its bones will have lost half their ^{14}C after 5730 years. After 11 460 years, half of that amount (now 25% of the original amount) will have decayed. Why is this important? Because by looking at the ratio of radioactive ^{14}C to stable ^{14}N, it is possible to determine the age of a fossil. If there is 12.5% of the radioactive isotope and 87.5% of the stable isotope, that means that three half-lives have gone by and the fossil is 17 190 years old. After a certain number of half-lives, there are so few ^{14}C atoms left that it is difficult to determine the age of the fossil with any accuracy.

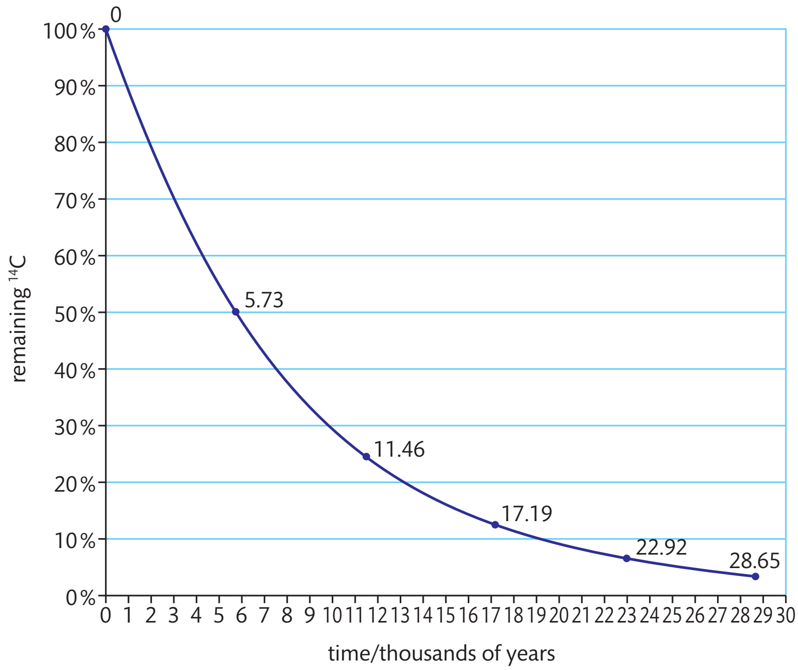
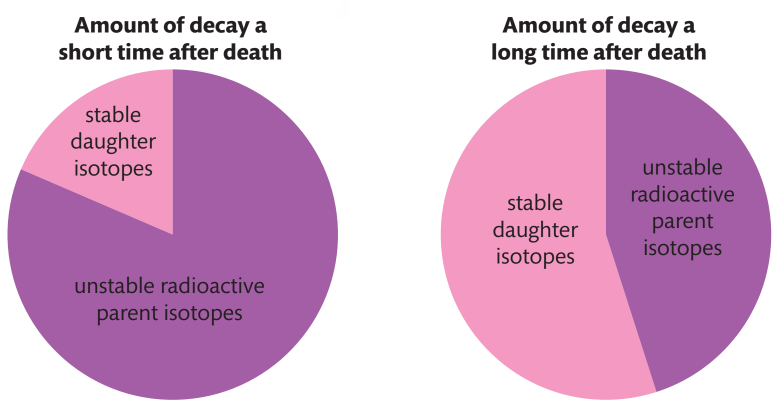


Figure 5.1 The effect of time on the proportion of radioisotope present in material containing carbon-14. The numbers on the curve show the passage of time (in thousands of years) through each successive half-life.

Fortunately, if there is insufficient ^{14}C, there are other radioactive isotopes that have much longer half-lives, such as ^{40}K (potassium-40). When the minerals in rocks crystallize from magma, they contain a certain percentage of ^{40}K ions. Once the minerals have hardened and crystallized, no more ^{40}K ions can be added. However, the number reduces as the radioisotope decays into more stable forms. Just as with ^{14}C, ^{40}K radiometric dating can be a useful tool in determining the age of a sample studied in a laboratory. Radiometric techniques with ^{40}K can be used to measure the age of rocks that formed from magma or lava between 100 000 years and 4.6 billion years ago.

Figure 5.2 The proportions of radioisotopes and stable daughter isotopes in a once-living organism indicate the passage of time since the organism died. The higher the proportion of stable daughter isotopes, the older the fossil.



Artificial selection and evolution

The fossil record is far from complete, but the science of breeding domesticated animals, for example cattle, horses, dogs, sheep, and pigeons, provides a good record of recent changes in heritable characteristics.

By watching which males mate with which females, animal breeders can see which characteristics the offspring will have. Of the offspring produced, not all will be equally valuable in the eyes of a breeder. Some cows produce better milk, other cows produce better meat; one breeder may be interested in better milk, another in better meat. Over the years, breeders have learned to choose the males and females with the most desirable genetic characteristics and breed them together.

This cow has been bred to have a straight back for easier birthing and long legs for better milking by mechanical pumps. She is a product of artificial selection by humans and she never existed in this form before human intervention.

After practising selective breeding for dozens and sometimes hundreds of generations, farmers and breeders realized that certain varieties of animals now had unique combinations of characteristics that did not exist before. Today, the meat or milk available to us is very different from that which was produced a few generations ago, thanks to the accumulation of small changes in the genetic characteristics of livestock chosen by breeders.

Although this is evidence that evolution is happening as a result of an accumulation of small changes over time, the driving force is, of course, human choice. The farmers and breeders choose which animals will reproduce and which will not. This is called artificial selection and it should be obvious that it is certainly not the driving force of evolution in natural ecosystems.

Evolution of homologous structures by adaptive radiation

Other evidence for evolution comes in the form of homologous anatomical structures, which are similar in form but which are found in seemingly dissimilar species. One of the most striking examples of this is the five-fingered limb found in animals as diverse as humans, whales, and bats. Such limbs are called pentadactyl limbs because 'penta' means five and 'dactyl' refers to fingers. Although the shape and number of the bones may vary, the general format is the same, despite the fact that the specific functions of the limbs may be very different. Darwin explained that homologous structures were

This is the front right fin of a southern right whale showing five articulated fingers..

not just a coincidence but evidence that the organisms in question have a common ancestor.

They may be of different sizes, and show varied morphology (shape), but the basic shape and position of the limb bones are the same. This would suggest that all five-fingered organisms have a common ancestor.

Whales, for example, could probably swim just as well with a different number of fingers in their front fins, so the fact that there are five suggests that there is a reason other than swimming efficiency: that of a common ancestry with other five-fingered organisms.

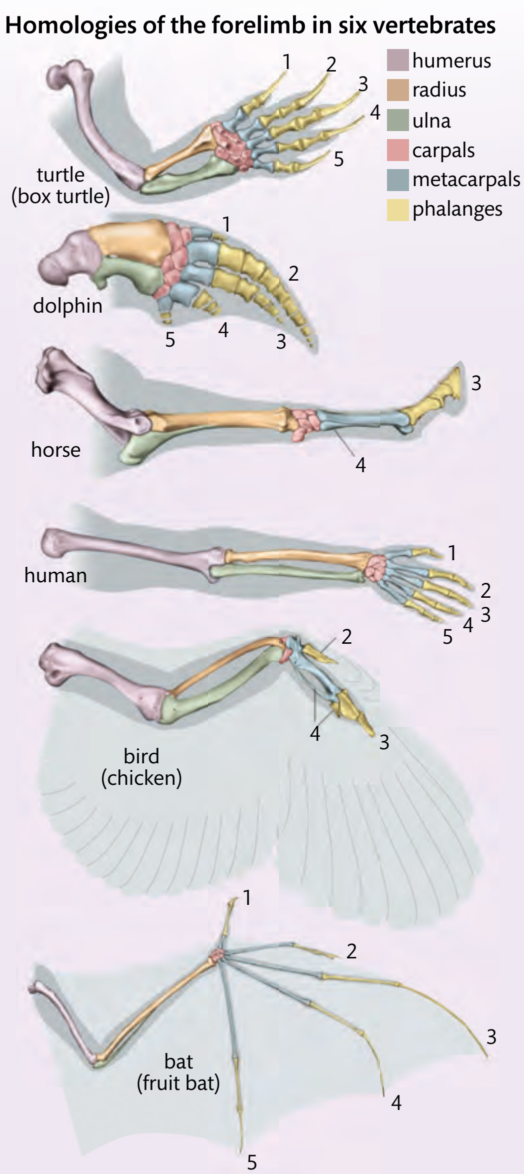


Figure 5.3 Pentadactyl forelimbs from various animals.

CHALLENGE YOURSELF

1 **(a)** Look at Figure 5.3 and complete Table 5.1.

Table 5.1

Characteristic	Bat	Bird	Human	Horse	Dolphin	Turtle
Number of digits (fingers)						
Description of phalanges (finger bones) (short/long, wide/narrow)						
Type of locomotion that the limb is best adapted for						

(b) There are two animals in Table 5.1 that have reduced their number of digits over the course of evolution. For these two animals, explain why it would have been a disadvantage to have kept all 5 digits. Limit your answer to the type of locomotion.

(c) Compare and contrast the salamander's forelimbs (Figure 5.4) to the organisms in Table 5.1. Be sure to address the idea of number of digits and locomotion.

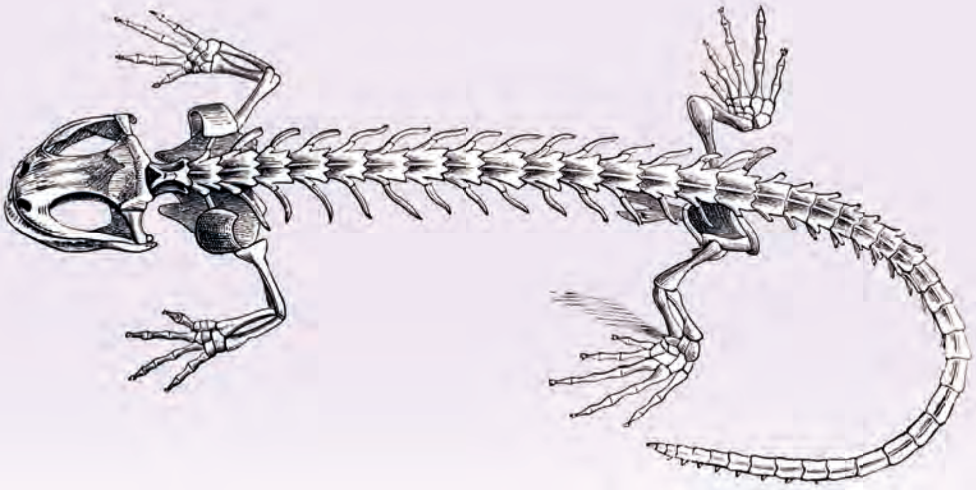


Figure 5.4 A salamander skeleton.

Species divergence

The process of an evolving population changing significantly enough so that the production of offspring with the original population becomes impossible is called speciation. In short, two populations of a species have diverged (separated), and a new species has evolved from an old one; both species will then continue on their separate ways.

Recall that a species must be able to freely interbreed with members of the same species to produce fertile offspring. If there has been a significant enough difference in two separated populations and they can no longer interbreed, a speciation has occurred.

Adaptive radiation

Adaptive radiation occurs when many similar but distinct species evolve relatively rapidly from a single species or from a small number of species. This happens as variations within a population allow certain members to exploit a slightly different niche in a more successful way. A niche is a position or role within a community of an ecosystem. By natural selection and the presence of some kind of barrier, a new species can evolve. A barrier separating populations might be a mountain range or a body of water.

An example of this are the primates found in Madagascar and the Comoro Islands off the south-east coast of Africa. Millions of years ago, without competition from monkeys or apes, lemurs on these islands were able to proliferate. Large numbers of offspring meant a greater chance for diversity.

Among the wide range of variation in lemur species, some are better adapted for living on the ground instead of in trees. Others are better adapted for living in lush rainforests, while some can survive in the desert. Most lemurs are active during the day (diurnal) but some are nocturnal. The reason why there are so many different species of lemur with different specialties is because of adaptive radiation.

Lemurs are primates found in Madagascar. They are a good example of adaptive radiation.

Not a single species of living lemur has been found anywhere else in the world. And yet fossils of their ancestors have been found on the continents of Africa, Europe, and Asia. What happened? It is believed that lemurs were not successful in competing with apes and monkeys, because as soon as traces of the latter start to become more prevalent in the fossil record, the lemur-like organisms become rare.

This would explain why continents and islands tend to have either prosimians (such as lemurs) or anthropoids (such as monkeys and apes), but not both types of primate. This is being confirmed today because more than a dozen species of lemur have become extinct recently, and many more are endangered, as a result of the activities of the most recently evolved anthropoid: humans.

Other examples of adaptive radiation can be seen in birds such as Darwin's finches (described in Section 5.2) on the Galapagos Islands and the Hawaiian honeycreepers. The honeycreepers have a wide variety of beak shapes, some of which are adapted exclusively to sip the nectar of flowers found only on Hawaii. It is believed that all the Hawaiian honeycreepers are the result of the adaptive radiation of a few members of one species that arrived on the islands.

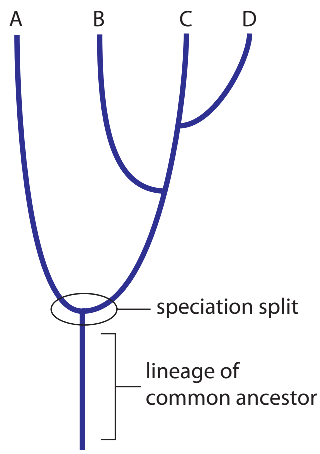


Figure 5.5 Speciation split shown on a phylogenetic tree.

Continuous variation and the concept of gradual divergence

In Figure 5.5, species A, B, C, and D come from a common ancestor. If any two of the species tried to mate, they would not successfully produce fertile offspring.

Figure 5.6 illustrates how one species can have various splits over time, creating a greater diversity between species. In some cases, the branches of the phylogenetic tree can become spaced so far apart that the species, although once closely related, do not physically resemble each other anymore. For example, when comparing a bird that has a long, thin beak to another with a short, fat beak, it is difficult to imagine that they are both descendants from the same species. And yet biologists have observed this in many species, notably ones that are spread over a wide geographical area.

From the example of the saltmarsh grass in the Nature of Science box, it is possible to see that, within a species that has a wide geographical distribution, there can be measurable differences in DNA. This is because the climate and soil are different in different locations. As a result, the populations adapt to the conditions available to them, and some versions of genes will be selected for and others will be selected against so that the populations are best adapted to their areas. This is called selective pressure. If this phenomenon continues to produce genetic differences over a long enough time, it is not difficult to imagine a point at which the differences between two separated populations are so great that they no longer belong to the same species. There comes a tipping point beyond which the differences outweigh the similarities and the two populations in question can no longer freely reproduce together. For example, if pollen from a northern species of marsh grass was used to pollinate flowers from a southern population, and no seeds or fertile offspring were produced, a speciation would have taken place.

NATURE OF SCIENCE

There is a species of plant that grows in coastal saltwater marshes called saltmarsh cordgrass, *Spartina alterniflora*. It plays an important role in providing habitat for organisms both above and below the water. The following investigation was carried out to determine whether differences in this plant along the eastern coast of the USA were the result of genetic variations or not. To test this, a group of scientists, led by Denise Seliskar, took samples of the cordgrass from three different states from different latitudes:

- Massachusetts (41° 34′ N)
- Delaware (38° 47′ N)
- Georgia (31° 25′ N).

They grew the plants in the same location at a research facility in Delaware and compared their growth in Delaware with how these plants grow in their native habitats. Notice how only one population is growing in its native state: the one from Delaware. The others have been moved either north or south of their native state. The investigators measured the growth of the plants over a 5-year period in various ways, including:

- biomass (how much dry organic material is produced in a year)
- height
- stem diameter.

The hypothesis was that, if there is no genetic variation within this species, then the three populations of plants from different latitudes will have similar growth patterns when grown in Delaware, because they are all given the same growing conditions of soil, water, light, and temperature.

The results, published in the *Journal of Ecology*, February 2002, were as follows. The population that originated from the south (Georgia) grew the most robustly. It showed the greatest biomass, height, and stem diameter. This is typical of plant growth in populations in southern latitudes where the climate is warmer. The northern-most population showed the least robust growth, matching values that were recorded in populations of its native Massachusetts. The population originally from Delaware showed no significant difference in growth from other populations in Delaware.

What can be concluded from this? Before you read on, can you reach your own conclusion? Look back at the hypothesis and decide if the data confirm or refute it.

Answer: the difference in growth refutes the hypothesis. The plants showed growth patterns similar to their native locations, suggesting that their DNA has a significant influence on their growth. The DNA imported from the southern latitude instructed the plants to grow larger, the DNA imported from the northern latitude instructed the plants to grow smaller. This indicates that there is variation in genetics from one geographical location to another.

This may not be the only explanation; perhaps there are others. However, in science, generally the principle of parsimony is applied: we look for the simplest, least convoluted explanation. For example, if we wanted to introduce the idea that an extra-terrestrial visitor came down to the experimental marsh where the plants were growing in order to somehow influence their growth with a special ray gun, we could. But that would not be parsimonious: it would be convoluted and would not be scientific because there is no evidence for it.

When scientific investigations are completed, usually they generate new questions or new ideas for further investigation. What do you think the investigators of the cordgrass would like to find out next?

Transient polymorphism

Within a population there is often more than one common form. Different versions of a species are referred to as polymorphisms (meaning many shapes) and can be the result of a mutation. One example of such an organism is *Biston betularia*, the peppered moth, which lives in temperate climates.

This species of moth can have a peppered (grey) form or a melanic (black) form; the melanic form is a rare mutation that usually affects less than 1% of a population. The grey form is well camouflaged against light-coloured surfaces, such as tree branches covered with lichens. One of the reasons why they are much more numerous in the population is that black moths are seen more easily against light-coloured lichens and thus are more frequently preyed upon by birds.

On close examination, you should be able to see two moths on the tree trunk covered in lichen.

Around the time of Darwin (1860s), a phenomenon was underway that continued for over a century: the industrial revolution. The melanic form of the peppered moth, called *carbonaria*, was increasing in number. Lichens, like the ones pictured on the tree in the photo, are very sensitive to air pollution, and the industrial revolution was producing chemicals, such as sulfur dioxide, that kill lichens. In addition, the air was filled with black soot from the large quantities of coal being burnt. As a result of this, the lichen-free, soot-darkened branches were a more difficult place for light-coloured peppered moths to hide: their camouflage simply did not work anymore. Birds eat moths and visual predation is facilitated when camouflage is poorly adapted.

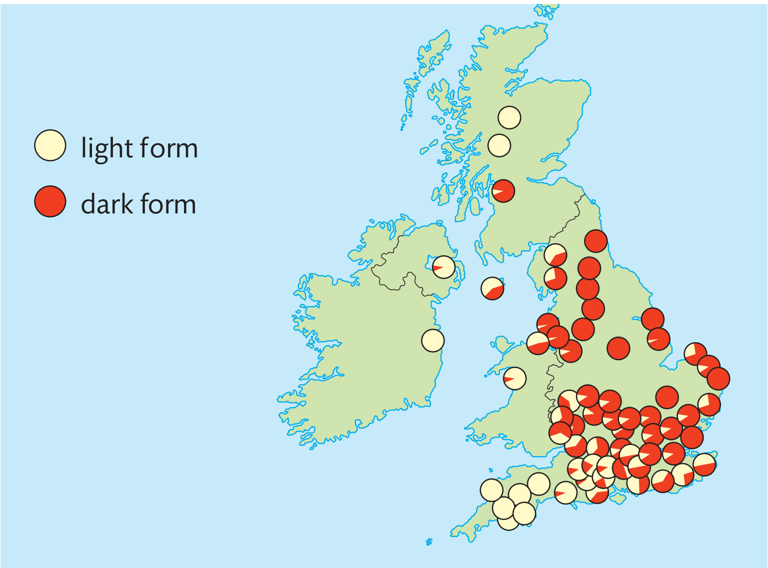


Figure 5.6 A map of the distribution of light-coloured and dark-coloured peppered moths in Great Britain under the influence of industrial pollution.

In places near industrial centres, the *carbonaria* moths accounted for 95–100% of all the peppered moths observed. Today, the percentages of *carbonaria* in a population rarely go above 30% and are often 0%. This is because of a significant improvement in air quality thanks to measures such as the UK Clean Air Act of 1956. These changes in the peppered moth population over time, from light-coloured to dark-coloured and then back again, is an example of transient polymorphism, temporary changes in the form of a species.

Worked example

Using the map in Figure 5.6 and the information presented about peppered moths during and after the industrial revolution in the UK, answer the following questions.

1 Statistics for peppered moths in the 1700s do not exist. Predict what the percentage of peppered moths would have been a century before Darwin lived, before the effects of the industrial revolution on trees.

2 **(a)** In the 1700s in a relatively non-polluted area where lichen is still growing on trees and soot is not a problem, a flock of birds comes to an area where there is a large number of grey peppered moths and only a very small number of black peppered moths. Explain why it is the black ones that have a higher chance of being eaten.

(b) What influence does this have on the population of dark-coloured moths?

3 Many decades later, the pollution has taken its toll on the lichen, and the soot in the air has blackened trees near industrial areas. Now when a flock of birds arrive to eat the moths, which kind gets eaten and why?

4 **(a)** Explain how it is possible that, by the 1900s, when the map in Figure 5.6 was made, most of the moths were dark-coloured.

(b) Explain how it is possible that now, in the 2000s, the population is back to being light-coloured.

Solutions

1 Because the mutation for melanism is very rare, it would be expected that the percentage of dark-coloured moths would be very low, certainly less than 10% and probably closer to 1%.

2 **(a)** The black ones will be eaten because they are easy to spot against a light background.

(b) This keeps the population of mutated dark moths at very low levels.

3 Now that the background colour has changed, the light-coloured moths will get eaten. This is because they are no longer able to hide against the darkened background.

4 **(a)** Because they were able to escape being eaten by birds, *carbonaria* moths were able to survive and pass on their genes to the next generation, something that was not possible before. In contrast, because the light-coloured moths were being spotted and eaten, they could no longer pass on their genes to the next generation. Over many generations, this process reduced the number of light-coloured genes from the population and favoured the allele for dark coloration. The same process happened for dozens of other species of moth.

(b) Ever since the Clean Air Act was passed in 1956, air quality around industrial zones of the UK has improved: there are fewer sulfur dioxides and less soot in the air. This has allowed the pollution-sensitive lichen population to return and allowed the bark on tree trunks and branches to return to their non-blackened colour. Now that the light-coloured moths can hide better and avoid being eaten, their numbers have increased. In contrast, *carbonaria* moths are no longer effectively camouflaged and get spotted and eaten by birds, reducing their presence in the population.

TOK

Trying to find out what happened in the past is the job of both historians and evolutionary biologists. Do they use the same methods to infer and deduce what the past was like? What counts as knowledge for an evolutionary biologist, and how is that similar or different from what counts as knowledge for a historian?

Natural scientists often use experimentation in laboratories to test out their hypotheses. And yet, it is impossible to carry out investigations such as breeding experiments with organisms that have gone extinct. How is the scientific method different for a scientist who studies fossils and evolution compared with a scientist who studies genetic traits in contemporary organisms?

TOK

Is the peppered moth a good example of evolution? The story of the peppered moth is a long one, involving many ups and downs. The data have been criticized, questions have been raised about whether bird predation is the only reason for the population change, and most of the photos of moths trying to rest or hide on tree trunks have been revealed as being staged: they are of dead moths stuck to the trunks for the purpose of the photo. Also, the idea of industrial melanism has been criticized as an example of evolution because no new species is formed: we started with a peppered moth and we finished with a peppered moth.

Although it is one of the most cited examples of modern evolution by natural selection, it has been suggested by some critics that it should be removed from textbooks because it is not a valid example and is based on sloppy science. Research this debate and trace the story's ups and downs. What are the arguments for and against the peppered moth as an example of evolution by natural selection? Should it continue to be used in classrooms as an illustration of how evolution works? When there are disagreeing sides, which one should we believe? What have you learned in Theory of Knowledge to help you to make your decision?

One of the most energetic proponents of neo-Darwinian ideas is the evolutionary biologist Richard Dawkins. In his writing, he points out the difficulty of applying the term species to organisms that lived in the past. For example, he asks his readers to picture a modern-day rabbit and imagine the rabbit's parents. There is no doubt that both of the parents and the offspring are all three of the same species, despite the fact that the offspring is not identical to its parents. We could probably be safe in taking this thought experiment back many generations and assume that, even though there are variations in each generation, there comes a time when the ancestor was significantly different from the modern rabbit. But how far do we go? It is difficult to know how many thousands of generations in the past we would need to study in order to declare that, at that point, that ancestor was, in fact, a different species.

Exercises

1 Define the term evolution.

2 Concerning species on Earth, describe two overall trends that can be seen in the fossil record.

3 Explain how selective breeding can be a good example of evolution by selection, even though it is not natural selection.

4 List two examples of adaptive radiation.

NATURE OF SCIENCE

Use theories to explain natural phenomena: the theory of evolution by natural selection can explain the development of antibiotic resistance in bacteria.

5.2 Natural selection

Understandings:

- Natural selection can only occur if there is variation amongst members of the same species.
- Mutation, meiosis, and sexual reproduction cause variation between individuals in a species.
- Adaptations are characteristics that make an individual suited to its environment and way of life.
- Species tend to produce more offspring than the environment can support.
- Individuals that are better adapted tend to survive and produce more offspring while the less well adapted tend to die or produce fewer offspring.
- Individuals that reproduce pass on characteristics to their offspring.
- Natural selection increases the frequency of characteristics that make individuals better adapted and decreases the frequency of other characteristics, leading to changes within the species.

Applications and skills:

- Application: Changes in beaks of finches on Daphne Major.
- Application: Evolution of antibiotic resistance in bacteria.

Guidance

- *Students should be clear that characteristics acquired during the lifetime of an individual are not heritable. The term Lamarckism is not required.*

The mechanism for evolution

Besides providing evidence for evolution, Darwin and Wallace suggested a mechanism for evolution: natural selection. How does this work? It all starts with the overproduction of offspring and the presence of natural variation in the population; then there is a struggle between competing varieties that leads to survival for some and death for others. This section will look at how evolution works through natural selection.

Variation within populations

Organisms such as bacteria reproduce simply by making a copy of their genetic information and then splitting into two using the process of binary fission. The result is that the second generation is identical to the first. In fact, many future generations will be identical or show very little change. There is little chance for the DNA to be modified.

The story is very different for species that reproduce sexually. When a cat has kittens, for example, each one is slightly different, or when a population of guinea pigs interbreeds there can be a wide variety of offspring.

Variation and success

Variation is closely related to how successful an organism is. A baby bird that has pigments that give it a colour matching its surroundings will have a better chance of not being seen by a predator. A fish with a slightly different shaped mouth might be able to feed from parts of a coral reef that other fish are not able to access. A plant that produces a different shaped flower might have a better chance of attracting insects for pollination.

It might seem obvious that a young bird with a colour that makes it very conspicuous to predators has little chance of surviving to adulthood. On the other hand, it might be more attractive to mates. A fish with an oddly shaped mouth may, in fact, be incapable of feeding adequately and die of starvation. A plant that produces flowers that are not attractive to insects will not have its flowers pollinated and will not produce any offspring.

As we have seen with the peppered moth, how frequent an allele is can change over time because of changes in the environment. This is only possible if there is more than one form of the allele. If the peppered moth did not have a mutation giving some members a dark colour, it is possible that certain populations would have been completely wiped out when their camouflage no longer worked

Variation can be seen in this population of guinea pigs.

against a dark background. In contrast, in bacteria, for example, there are essentially no differences within a population: all members of the population are genetically identical copies of each other. This means that if an adverse change happened in the environment, such as a change in pH, if one bacterium is susceptible to the change in pH and dies, they in fact all die because they all have the same vulnerability. In species where there is variation, a change in the environment will eliminate some but not all members of the population. This is why variation is a strength and not a weakness in a population. We will see how this works as this section continues.

The idea of eugenics is that, if human breeding is controlled, it could improve the population by favouring desirable characteristics and eliminating undesirable ones. This is highly controversial, and historical applications of it have been widely criticized. Trying to breed a 'superior race' where everyone has the same characteristics is contradictory to the concept Darwinian evolution is based on: variety. The resilience of a species is highly dependent on variety.

Mutation, meiosis, and sexual reproduction

There are three main mechanisms that give organisms in a species their variation:

- mutations in DNA
- meiosis
- sexual reproduction.

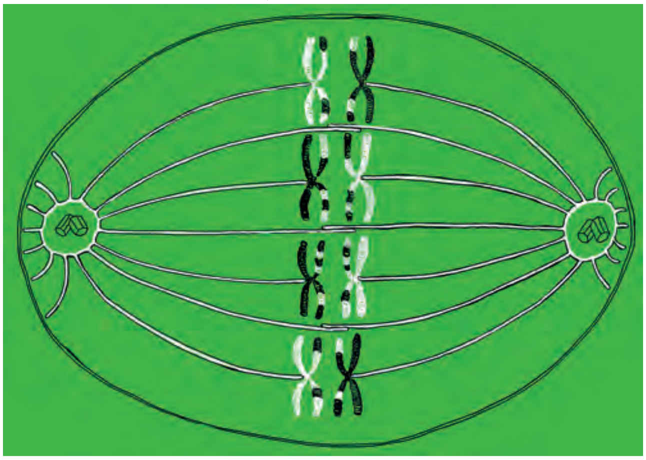
Mutation

Mutations can sometimes produce genes that lead to genetic diseases, and can have devastating effects on the survival of some individuals in a species. However, sometimes a mutation can produce a characteristic that is advantageous, perhaps a slightly faster growth rate for a tree or better frost resistance for a plant. A beneficial mutation for a bird or insect might result in a different camouflage that better matches a changing habitat. In each generation, only a few genes mutate, and most mutations produce effects that are neither useful nor harmful. As a result, sexual reproduction is a much more powerful source of variation in a population because thousands of genes are mixed and combined. But sexual reproduction is only possible thanks to meiosis.

Meiosis

Meiosis, you will recall from Section 3.3, enables the production of haploid cells to make gametes (sperm cells and egg cells). At the end of meiosis, four cells are produced that are genetically different from each other and only contain 50% of the parent cell's genome. An individual that reproduces sexually can produce huge numbers of possible combinations of half the genetic material it possesses, thanks to meiosis. For example, in a woman's lifetime, it is nearly impossible for her to produce the same egg twice. This is why, no matter how many pregnancies she has, she will never have the same child twice from two different pregnancies. The only way identical humans have ever been formed is when two embryos are formed from a single egg, i.e. identical twins, and even then there are slight genetic differences between the siblings.

Figure 5.7 Random orientation during metaphase I and crossing-over (shown by banding on sister chromatids) promote variety in the gametes. Each sister chromatid will separate into separate haploid cells at the end of meiosis (see Section 3.3).



The variety in gametes comes mainly from the process of random orientation during metaphase I. The lining up of chromosomes in a random order is like shuffling a deck of cards, and it greatly promotes variety in the egg cells or sperm cells produced. In addition to this, the process of crossing-over contributes to the shuffling of genetic material and further increases the genetic variety.

Sexual reproduction

As we have seen, asexual reproduction such as binary fission in single-celled organisms does not promote variety in the population. Generally speaking, in an asexually reproducing population, all the members of the population are identical. There may be rare exceptions of mutations or gene transfer, but overall such populations can remain identical generation after generation. The consequence for this is that natural selection only leaves two choices for the population: survive or die. One of the causes of the Great Famine in Ireland in the mid-1800s was that the potatoes had been produced asexually and were all clones, making them all susceptible to the same infection by a microorganism that causes potato blight. This also illustrates that if there is no variety in a population, there is a very limited number of outcomes: the whole population either survives or dies. This is why variety is so important to natural selection. More possibilities lead to more possible outcomes: some members of the population survive without any adverse effects, others may be affected in a negative way but still survive, and others may die. Variety in the population allows some individuals to be better adapted to whatever change in the environment is harmful to others.

Part of what determines whether or not a female animal becomes pregnant is that all the conditions must be right inside her body, and that sperm cells must be present at the opportune moment when an egg is ready. Of the many sperm cells that may be present, only one will penetrate the egg. In determining exactly which sperm cell and egg will meet and fuse together, a certain amount of chance and luck are involved. In non-human primate species, such as chimpanzees, for example, when a female is fertile, many males may copulate with her to try to impregnate her. In such a scenario, it is impossible to guess which male's sperm cells will successfully fertilize her egg. It is largely up to chance. In flowering plants, which bees will land on which flower of a population, with what pollen from another flower in that population, is also a matter of chance.

Which of these yellow pollen grains on the bee's body will pollinate the next flower it visits?

There are three main sources for variation in a population:

- mutations in DNA
- meiosis
- sexual reproduction.

But make no mistake, although these two mechanisms for increasing variety (meiosis and sexual reproduction) rely on chance, it would be unfair to conclude that all of life is just a game of chance. As we will see, natural selection has another side to it that has little to do with chance and allows for systematic accumulations of small changes to produce highly adapted forms of life.

To adapt or not to adapt?

Although it is possible for some organisms to adapt to changes in their environment within their lifetimes, this is not the kind of adaptation referred to in evolution. For example, just because an individual hare can shed its brown fur and grow white fur for the winter in order to be better camouflaged against the snow, does not mean that the individual has 'evolved' from one season to the next. Evolution happens to populations and its effects are only visible over many generations.

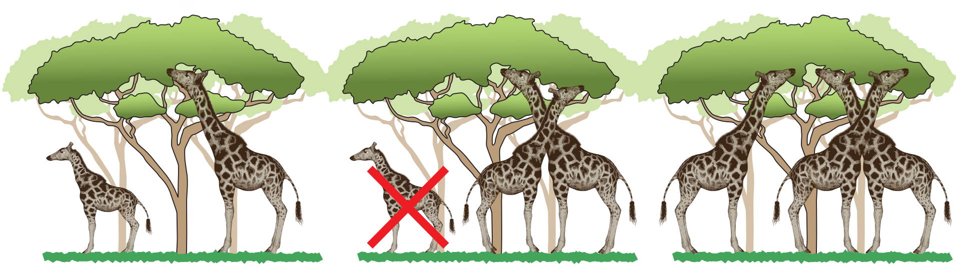
The adjective adaptation and the verb to adapt are freely used when talking about evolution. However, the terms have very precise meanings within the framework of natural selection and should not be confused with other uses of the term, notably for human behaviour. For example, humans can consciously decide to adapt to a situation: think of a student learning the language of a country he or she has just moved to, or of a person who is used to driving his or her car on the right-hand side of the road and rents a vehicle in a country where driving is done on the left-hand side and so adapts very quickly to left-hand driving. These are conscious adaptations made by individuals. In nature, the vast majority of adaptations referred to in evolution and natural selection are unconscious adaptations made by populations rather than by individuals.

One example we have already seen is the adaptation of the peppered moth populations over time before and after the industrial revolution. On light-coloured backgrounds, the grey moths were better adapted, whereas on dark-coloured backgrounds, the black moths were better adapted. Another example is that a giraffe's neck is well adapted for reaching leaves high up in trees. If a giraffe was born with a mutation that gave it a short neck, it would have trouble competing with other giraffes to get leaves. A short neck is an example of a characteristic that is not well adapted for a giraffe's lifestyle.

An organism that has characteristics that are well adapted for its environment is said to be fit. The characteristics it possesses fit well into its environment.

Natural selection tends to eliminate from a population individuals that show low fitness, whereas the fittest individuals in a population have a higher likelihood of surviving. Although there are rare exceptions, individuals are usually incapable of changing themselves to adapt. For example, a giraffe born with a short neck cannot stretch its neck to get a longer one. Rather, because it will have difficulty feeding itself and surviving, the chances are very low that it will find a mate and reproduce to be able to pass on its genes to the next generation. Hence the alleles for making a short neck are not found in the giraffe population.

Figure 5.8 The giraffe's long neck explained by natural selection.



Ancient population with variation in neck lengths. Giraffes with longer necks can reach more food and have a better chance of survival. Those born with shorter necks find less food and have lower chances of survival.

After many generations, the genes for longer necks are passed down more successfully than the genes for shorter necks. The population sees more and more long-necked giraffes and fewer and fewer short-necked giraffes until they all have long necks.

Too many offspring

Darwin noticed that plants and animals produce far more offspring than could ever survive. Plants often produce hundreds or thousands more seeds than necessary to propagate the species. Mushrooms produce millions more spores than ever grow into new mushrooms. A female fish lays hundreds or thousands of eggs but only a handful survive to adulthood.

This seems paradoxical, because the production of seeds, spores, and eggs involves using energy and nutrients that also are vital to the parents' survival. Why are such valuable resources squandered on so many excess cells that are never going to give rise to viable offspring? The answer is to maximize the chances of some offspring surviving, even if the survival rate is less than 1%.

Having too many offspring and not enough resources is a problem of supply and demand. There is high demand for water, space, nutrients, and sunlight, but there is a limited supply. The consequence is competition for these resources in order to stay alive. This is called the struggle for survival.

Many species of animal are territorial and possessive of their food supplies: they spend a great deal of time and energy defending their resources. Trees, too, defend their resources, by having active compounds such as tannins and alkaloids in their trunks to ward off attackers such as insects. All these adaptations make it difficult for a new arrival to find enough resources. As a result, parents send out dozens, hundreds or thousands of potential offspring into the world. Parent organisms that do not produce as many may find the probability of their genes being passed on greatly reduced.

Adaption and survival

Evolution is not just based on chance. In a situation where there are too many organisms for limited resources, it is obvious that some individuals will succeed in accessing those resources and the rest will fail. In other words, there is a selection. Exactly which individuals survive and which ones do not is not based on chance alone but determined by their surroundings and the compatibility of their characteristics with those surroundings. The steps of evolution by natural selection are outlined below.

- Overproduction of offspring and, in those offspring, natural variation as a result of genetic differences (e.g. body size, morphology, pigmentation, visual acuity, resistance to disease). In the offspring:
  - useful variations allow some individuals to have a better chance of survival (e.g. hiding from predators, fleeing danger or finding food)
  - harmful variations make it difficult to survive (e.g. inappropriate colour for camouflage, heavy bones for birds, having such a big body size that there is not enough food to survive).
- Individuals with genetic characteristics that are poorly adapted for their environment tend to be less successful at accessing resources and have less chance of surviving to maturity.
- Individuals with genetic characteristics that are well adapted for their environment tend to be more successful at accessing resources and have a better chance of surviving to maturity. Such individuals are said to have better fitness.
- Because they survive to adulthood, the successful organisms have a better chance of reproducing and passing on their successful genetic characteristics to the next generation.

CHALLENGE YOURSELF

One quantitative study done over a 30-year period by Rosemary and Peter Grant showed differences in beak sizes of ground finches, *Geospiza fortis*, from two islands of the Galapagos: Daphne Major and Santa Cruz. You can learn more about this study through an online exercise including analysis of the data they collected. You can find a link to this activity in the hotlinks box at the end of this section.

- Over many generations, the accumulation of changes in the heritable characteristics of a population results in evolution: the gene pool has changed.

As you can see, it is impossible to sum up all these concepts in one catchy phrase such as 'the law of the jungle'. Although Darwin himself eventually adopted the phrase 'survival of the fittest', the idea of evolution by natural selection is more complex than that. In addition, many people have the misconception that what Darwin said was 'only the strongest survive'. This is simply not true.

The theory of evolution by natural selection is full of subtleties. This could be one of the reasons why it is so widely misunderstood by the general public. For example, an organism that is well adapted to its environment is not guaranteed success, it simply has a higher probability of survival than another that is less well adapted. Dinosaurs such as the sauropods were the biggest, strongest animals ever to walk the planet. But they did not survive the environmental changes that drove them to extinction. In fact, the fossil record indicates that more than 99.99% of all life that has ever existed on Earth is now extinct.

Plover eggs show adaptations that have been acquired by natural selection. The colour and spots help to camouflage them from predators.

In the photo of plover eggs, the colours and speckles act as effective camouflage, making these eggs difficult to spot by predators. Plover chicks are also speckled for camouflage. If a mutation caused a shell to be bright white and/or the chicks to be bright yellow, the mutation would be unlikely to be an advantage to this species. On the contrary, a white egg or yellow-bodied chick would attract the attention of a predator, the egg or chick would be eaten, and the possibility of passing on the mutation to the next generation would be zero.

It is crucial that you remember Darwin's steps of how natural selection leads to evolution. Be sure to memorize the following: (1) overproduction of offspring; (2) variation within the population, as a result of meiosis, sexual reproduction, and mutations; (3) struggle for survival, because there are not enough resources for all members of the population; (4) differential survival, those individuals best fit for their environment tend to survive better; and (5) reproduction, those who survive can pass on their genes to the next generation. It is through these steps that populations evolve. Remember that, even though the changes can be observed in individuals from generation to generation, what is of importance is what happens at the level of populations rather than at the individual level.

Passing on successful characteristics

It should be obvious that an individual that never reaches maturity will not be able to pass on its genes to the next generation. An individual that is poorly adapted to its environment, such as an insect with deformed mouthparts that make it impossible to feed, is not likely to survive to adulthood and be able to reproduce.

On the other hand, an individual showing high fitness has a better chance of surviving until adulthood and reaching maturity. Individuals that reach maturity have the possibility of reproducing and passing on their genetic material. Again, there is no

guarantee that fitness will allow survival or that survival will allow reproduction, but, in order to reproduce, one thing is certain: survival must come first. Remember the example of the giraffes: those who were born with the alleles to make necks long enough to access better food sources had a greater chance of surviving and passing on those alleles, whereas those with short-neck alleles had more trouble finding enough food and were less frequently able to survive to pass on their alleles.

Natural selection and the frequency of characteristics

Pesticide resistance in rats and multiple antibiotic resistance in bacteria are both carefully studied modern examples of natural selection. What is striking about these examples is their rapidity. Although evolution is generally considered to be a long-term process, the mechanism of natural selection can sometimes be quick, taking place over months, years or decades, rather than millennia. As you read the descriptions below, see if you can identify the main features of how natural selection works: variation in the population making some individuals better suited for their environment than others, overproduction of offspring leading to a struggle for survival, differentiated survival because some die and some live, and, finally, the passing on of successful traits to the next generation.

Pesticide resistance in rats

Pesticides are chemicals that kill animals that are regarded as pests. Farmers use them to eradicate pests, such as rats that eat their crops. Consider the following scenario.

1. Once applied in the fields, pesticides kill all the rats … or so the farmer thinks.
2. As a result of natural variation, a few rats from the population on the farm are slightly different and are not affected by the poison.
3. The resistant rats are better adapted to survive in the presence of the pesticides and now, thanks to the farmer's actions, have no other rats to compete with for a food supply. Hence, they thrive and reproduce, making a new population in which some or all of the members possess the genes that give resistance to the pesticide.
4. Seeing rats again, the farmer puts out more of the original poison; this time fewer rats die. Because the characteristic of poison resistance was favoured in the rat population, it is now much more common in the population.
5. To kill the resistant rats, a new pesticide must be used.

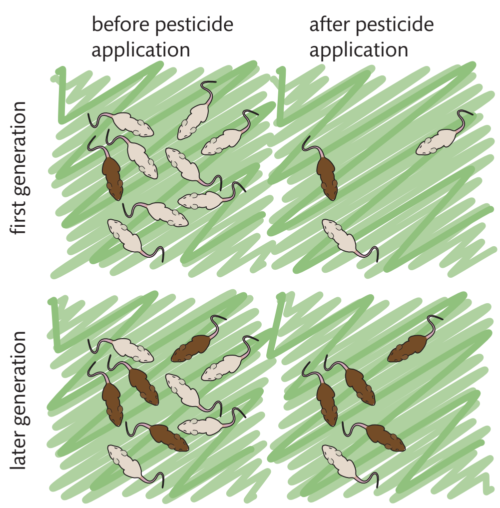


Figure 5.9 How populations of pests such as rats develop resistance by natural selection. Notice the difference in the number of resistant rats before the first pesticide application and after the application.

It is important to note that, in this example, we cannot say that the rats become immune to the poison. Although the term 'immunity' is sometimes interchangeable with the term 'resistance', that is not the case here. Immunity develops within the lifetime of an individual; pesticide resistance is a change that evolves in a population from one generation of rats to the next generation. The evolution happened in the population, not in any single rat. A rat is either born with a susceptibility to be killed by the pesticide or is born with resistance to it. An individual rat cannot adapt and evolve into a resistant rat.

It is also important to note that the characteristics that change and evolve over time must be heritable (passed on by genes). An example of this is that farmers have been cutting off the tails of sheep for many centuries and yet sheep continue to be born with long tails. In other words, characteristics acquired during an organism's lifetime cannot be passed on to the next generation and so do not have a part in the theory of evolution by natural selection.

Sheep are still born with long tails, despite being removed by farmers for countless generations.

Antibiotic resistance in bacteria

Antibiotics are medications such as penicillin that kill or inhibit the growth of bacteria. They are given to patients suffering from bacterial infections. They are also sometimes given to people who are suffering from something else and, because their immune system is weak, are at a greater risk of a bacterial infection. However, overuse of antibiotics can lead to the production of resistant strains of bacteria.

Antibiotic resistance in bacteria develops in several steps. Consider the following scenario.

1. A woman gets a bacterial infection such as tuberculosis.
2. Her doctor gives her an antibiotic to kill the bacteria.
3. She gets better because the bacteria are largely destroyed.
4. By a modification of its genetic makeup, however, one bacterium is resistant to the antibiotic.
5. That bacterium is not killed by the antibiotic and it later multiplies in the patient's body to make her sick again.

6 She goes back to the doctor and gets the same antibiotic.

7 This time, no result: she is still sick and asks her doctor what is wrong.

8 The doctor prescribes a different antibiotic that (hopefully) works. But if the population of bacteria continues to acquire mutations, new strains could show resistance to all the antibiotics available.

Because bacteria reproduce asexually, genetically they generally do not change very often. However, there are two sources of possible change in the genetic makeup of bacteria:

- mutations (as seen in Section 3.1)
- plasmid transfer.

Plasmid transfer involves one bacterium donating genetic information to another in a ring of nucleotides called a plasmid. Both the donating and receiving cells open their cell walls so that the genetic material can pass from the donor to the receiver.

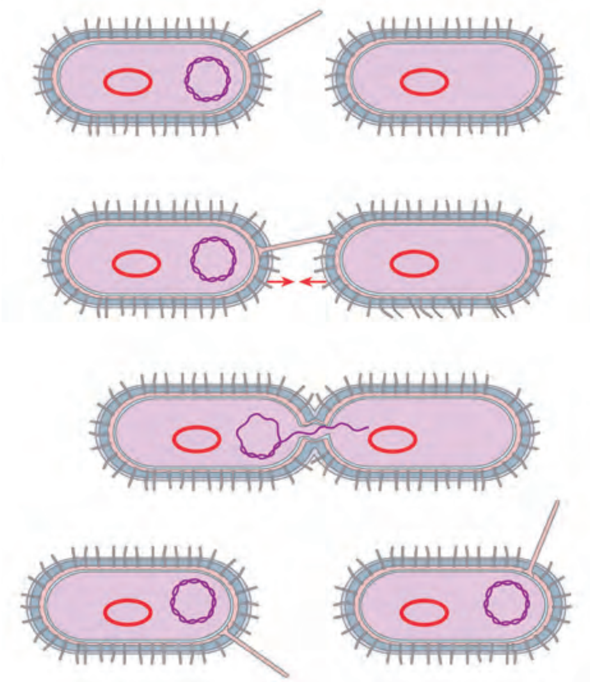


Figure 5.10 The bacterium on the left is passing genetic information to the bacterium on the right in a process called plasmid transfer.

The development of antibiotic-resistant bacteria has happened in several cases. New strains of syphilis, for example, have adapted to antibiotics and show multiple resistance. Some strains of tuberculosis are resistant to as many as nine different antibiotics. There is no cure for people who get sick from such super-resistant germs, and they must rely on their immune system to save them.

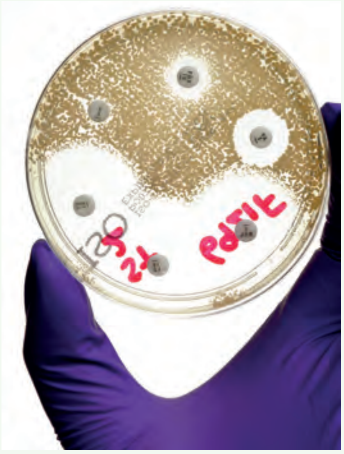
Finding new antibiotics would only be a temporary solution, and pharmaceutical companies cannot find new medications fast enough to treat these super-resistant germs. As a result, the best way to curb their expansion is to make sure that doctors minimize the use of antibiotics and that patients realize that antibiotics are not always the best solution to a health problem.

Notice how the two examples above are good illustrations of how we can use a scientific theory to explain observed phenomena. As stated at the beginning of the section on evolution, once the theory of natural selection is understood, it allows us to understand a variety of natural phenomena.

Antibiotic-resistant pathogens such as MRSA are causing hospitals and clinics all over the world to rethink their standards of hygiene. MRSA stands for methicillin-resistant *Staphylococcus aureus*. Health officials are concerned that, without internationally coordinated efforts, these super bugs could be spread from one country to another as patients get transferred across borders for treatment. What kinds of international regulations exist concerning antibiotic use, quarantine, and other such practices, that either encourage or limit the spread of resistant bacteria?

NATURE OF SCIENCE

A *Staphylococcus* bacterium discovered in a hospital is suspected of being resistant to a certain number of antibiotics. To test this hypothesis, the bacterium is introduced into a Petri dish along with small disks of paper that are soaked in different types of antibiotic. In an experiment like this, when the colonies of bacteria grow close to the disks, they show resistance to the antibiotic, whereas when wide, clear circles of inhibited bacterial growth are present, they show that the antibiotic is stopping the bacteria the way it should. Can you interpret the results of the experiment shown in the photo?



Testing for antibiotic resistance.

In the photo, the four disks of different antibiotics nearest the technician's hand show rings of growth inhibition, suggesting an effective control of the colony of bacteria by the medications. However, the two disks at the top furthest away from the hand (top centre and top left) have allowed the bacterial colony to grow dangerously close. This suggests that this strain of *Staphylococcus* is resistant to those two antibiotics and cannot be stopped by them. Doctors use such tests to help decide which medications to prescribe. In this case, they should prescribe the antibiotics that the bacteria do not show a resistance to, preferably the three at the bottom of the image.

This resistant bacterium is part of a growing number of super bugs, among which we find MRSA. They have evolved because of the way humans use antibiotics.

TOK

In some countries, there is a very intense debate about whether the concept of evolution should be taught in schools. To support the critics of evolution, there are thousands of websites and publications that carefully try to dismantle and disprove the arguments of evolutionary biologists. What criteria are used to determine whether these criticisms are valid or not? What kind of evidence would be necessary to refute Darwin's theory?

Evolution by natural selection is a multi-step process. Some steps involve chance, such as variation in a population, or certain aspects of sexual reproduction, such as which gametes participate in fertilization and which do not. However, the presence of a particular characteristic in a population is not purely up to chance. It's not just lucky, for example, that falcons have excellent vision or that dolphins are capable of echolocation. It's not by pure happenstance that flowers have adaptations perfectly suited to their insect pollinators, or that certain bacteria become resistant to the antibiotics we try to fight them with. Natural selection favours useful adaptations and selects against harmful ones in a way that is not based on luck and chance, but on fitness. Heritable changes are passed on from generation to generation, and accumulate over time so that each population either fits its environment, adapts accordingly, or dies out.

Design an experiment simulating natural selection

Safety alerts: When choosing objects used for simulating mouthparts or food, avoid objects that are too sharp, such as certain types of tweezers or thumb tacks. Also, if several competing organisms are trying to get food from the same food source, such as a tray or plate, you should not peck at your competition with your mouthparts.

In order to simulate natural selection between organisms obtaining food, design a lab in which some form of pinchers or clips are used as 'mouthparts' and a variety of small objects are used as 'food'. Some form of 'stomach' needs to be established, such as a Petri dish placed at a particular distance from the food source.

- Examples for mouthparts: tweezers, clothespins, wooden tongs, or even chopsticks.
- Examples for food: dry chickpeas or kidney beans, dry grains of rice, marbles, paper clips, or coins. To make it more challenging, calorie values could be given so that the most difficult food to pick up is worth the most calories.

The investigation should involve participants simulating organisms using their mouthparts (the tweezers, for example) to fill their stomachs with food. Those who attain a minimum requirement of food are allowed to continue to the next round; those who do not are eliminated by natural selection. In effect, the simulated organism dies of hunger.

The designed investigation must show a certain amount of variation of mouthparts within the population of feeding organisms. The investigation must also limit the time and the resources available. Natural selection should be demonstrated by determining a minimum amount of food collected in the organism's stomach within the time limit. Rules must be established to avoid cheating such as holding the stomach under the desk and pushing food into it.

Just as with any designed investigation, be sure to start with the aim, research question, and three types of variables, before establishing the step-by-step method. See the Internal assessment chapter in the eBook for help with variables. Some trial runs will probably be necessary to refine your method.

Exercises

5 Besides mutation, list two factors that are responsible for increasing variation in a population.

6 Distinguish between artificial selection and natural selection.

7 Ground-nesting birds such as grouse lay their eggs in a nest made on the ground. The eggs of this species are generally speckled dark brown. If a mutation occurred causing the eggs to be brightly coloured, how would the change in colour affect their chances of survival?

8 Explain how a population of insects could develop resistance to the insecticides sprayed on them.

To learn more about evolution, go to the hotlinks site, search for the title or ISBN, and click on Chapter 5: Section 5.2.

5.3 Classification of biodiversity

Understandings:

- The binomial system of names for species is universal among biologists and has been agreed and developed at a series of congresses.
- When species are discovered they are given scientific names using the binomial system.
- Taxonomists classify species using a hierarchy of taxa.
- All organisms are classified into three domains.
- The principal taxa for classifying eukaryotes are kingdom, phylum, class, order, family, genus, and species.
- In a natural classification, the genus and accompanying higher taxa consist of all the species that have evolved from one common ancestral species.
- Taxonomists sometimes reclassify groups of species when new evidence shows that a previous taxon contains species that have evolved from different ancestral species.
- Natural classifications help in identification of species and allow the prediction of characteristics shared by species within a group.

NATURE OF SCIENCE

Cooperation and collaboration between groups of scientists: scientists use the binomial system to identify a species rather than the many different local names.

Applications and skills:

- Application: Classification of one plant and one animal species from domain to species level.
- Application: Recognition features of Bryophyta, Filicinophyta, Coniferophyta, and Angiospermophyta.
- Application: Recognition features of Porifera, Cnidaria, Platyhelmintha, Annelida, Mollusca, Arthropoda, and Chordata.
- Application: Recognition of features of birds, mammals, amphibians, reptiles, and fish.
- Skill: Construction of dichotomous keys for use in identifying specimens.

Guidance

- *Archaea, Eubacteria, and Eukaryote should be used for the three domains.*
- *Members of these domains should be referred to as archaeans, bacteria and eukaryotes.*
- *Students should know which plant phyla have vascular tissue, but other internal details are not required.*
- *Recognition features expected for the selected animal phyla are those that are most useful in distinguishing the groups from each other, and full descriptions of the characteristics of each phylum are not needed.*
- *Viruses are not classified as living organisms.*

The binomial system of names for species

You have a name that you were given when you were born, but you also have a scientific name based on your species: *Homo sapiens*. This system of naming organisms using two names is called binomial nomenclature. 'Bi' means two, 'nomial' means name and 'nomenclature' refers to a system used to name things.

Myrmecophaga tridactyla is a name that literally means 'eater of ants' plus 'with three fingers'. In case you have not guessed, it refers to an anteater, and this one happens to be the giant anteater of Central and South America. In fact, the animal really has five fingers, but they are hard to see because the animal walks on its front knuckles.

Figure 5.11 The giant anteater, *Myrmecophaga tridactyla*.

The first name in the binomial nomenclature system is always capitalized and it refers to the genus; the second name always begins with a small letter and refers to the species. Both are always written in italics when typed, or underlined when written by hand. Most words used in binomial nomenclature are Latin or Greek in origin. For example, *Lepus arcticus* is the scientific name for the Arctic hare; both terms come from Latin. This is why the term Latin name is often used, although this is an oversimplification because other languages are also involved.

This system of naming organisms was consolidated and popularized by the dynamic Swedish naturalist Carolus (Carl) Linnaeus. In his book *Systema Naturae* (*The Natural World*, 1735), he listed and explained the binomial system of nomenclature for species that had been brought to him from all over the world. Although he was not the first to use the idea of genus (plural genera), he popularized its use along with the species name in a consistent way.

Today, there are hundreds of specialists who, like Linnaeus, describe and name new species. When it comes to classifying animals, for example, every 4 years the International Congress of Zoology takes place in a different city; it is an event during which animal experts from all over the world share and discuss their findings about animal behaviour, genetics, and classification. The dates and locations of the 19th–22nd congresses are:

- 2004 Beijing, China (XIX)
- 2008 Paris, France (XX)
- 2012 Haifa, Israel (XXI)
- 2016 Japan (XXII).

Zoologists started these conferences in Paris in 1889, on the occasion of the World Fair that year, the one that inaugurated the Eiffel Tower. Although many things are discussed as such congresses, one of the topics that comes up is the binomial nomenclature system. Decisions need to be made about new organisms that have been recently discovered or old organisms that might need reclassifying because of new evidence about their ancestry.

There are three main objectives to using binomial nomenclature and its associated rules: (1) to be sure that each organism has a unique name that cannot be confused with another organism; (2) so that that the names can be universally understood, no matter what nationality or culture is using the name; and (3) so that there is some stability in the system by not allowing people to change the names of organisms without valid reasons.

One result of discussions between many zoologists has been the International Code of Zoological Nomenclature (ICZN), which makes the rules about how to classify and name animals. There are also rules about how to use the names and properly cite them in research papers. In cases where two different animal species have been given the same name, there is a rule that the oldest valid publication of the name should be used. This is referred to as the principle of priority and is taken very seriously. This principle is applied when the same species is accidentally named twice by two different experts with two different names; again the first one gets priority.

In the days when there were fewer rules, some scientists named unsightly or offensively smelling organisms after people they considered to be their enemies. This is no longer allowed.

In addition to these zoological congresses to discuss animals, there are international congresses for many forms of life, including algae, fungi, plants, and bacteria, and each one has their own code for nomenclature. In this way, when a biologist discovers a new organism, he or she has detailed guidance from such codes about where to place the organism in the tree of life, a metaphor used to denote the branches leading back to a common ancestor.

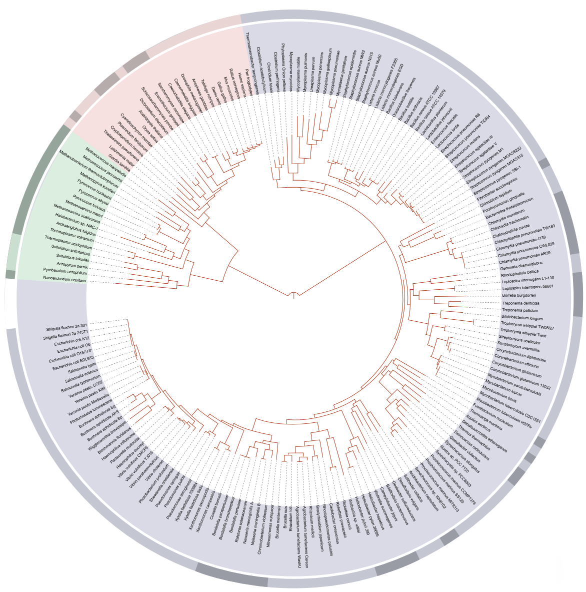


Figure 5.12 A diagram from the interactive Tree of Life online tool. Notice how, unlike other 'tree' diagrams, there is no summit on this circular diagram. All organisms alive today have evolved for the same number of years: we are all survivors. Species names are given around the outside of the circle. Find out more about this by going to the hotlinks site and clicking on Chapter 5: Section 5.3.

International cooperation and communication are key concepts in science. It is important that scientists are able to share their ideas, discuss developments, and make decisions together about how to communicate better and share knowledge. The continuing development of the binomial nomenclature system is an example of scientists recognizing and overcoming the confusion that would occur if each biologist used the local names of species in his or her own language. Although the original purpose of the internet was to serve military needs, the first major non-military group of individuals to see the usefulness of such a system was scientists.

Naming new species

Humans like to see similarities and differences in the objects that surround them: hot or cold, delicious or foul-tasting, dangerous or safe, and so on. In the early days of classification, all known organisms were classified into only two kingdoms: plants and animals.

As the centuries went by, and as the study of biology became more systematic, tens of thousands of new species were discovered in forests, deserts, and oceans, some of which showed characteristics of both plants and animals, and some of which were not like either plants or animals. For example, mushrooms grow on the forest floor the way plants do, and yet they do not have leaves or roots and they do not photosynthesize: they get their energy from digesting dead organic matter. So mushrooms cannot be classified as plants, because they are not autotrophs, but they are certainly not animal-like either, one reason being that they have cell walls made of chitin.

With the invention of the microscope in the mid 1600s, many new creatures were discovered that were nothing like plants or animals. In effect, the microscope revealed that there is an entire world of invisible organisms living throughout the biosphere.

If a botanist finds a new species of orchid, for example, he or she would have to describe the plant, describe the location it was found in, name it using the proper rules of binomial nomenclature as set out by the International Code of Botanical Nomenclature (ICBN), and publish the findings in a publically accessible publication. In addition, it is important to put a sample specimen in a public location where other botanists can examine it. Such an example specimen is called a holotype. One of the rules of nomenclature is that a scientific name is not considered valid if a specimen is not available for verification. In some circumstances, a precise illustration is acceptable, but it is always better to make a holotype available. Proposing a name for mythical creatures no one has ever captured, for example, is not accepted.

On the other hand, it is perfectly acceptable to name a well-described organism that no longer exists, such as an extinct dinosaur. Usually the holotypes of fossilized species are kept in museums, but simply finding a fossil, labelling it and putting it on display in a museum does not count as officially naming it. Again, the name would have to be published along with a description in a reputable scientific publication.

This fossil skull was discovered by Mary Leakey in 1959 at Olduvai Gorge, Tanzania. It is the holotype for the extinct hominid species *Paranthropus boisei* and the skull is now at the Natural History Museum in London.

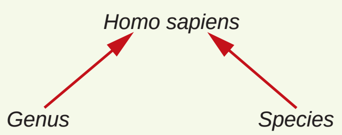
Examples of binomial nomenclature

Sometimes scientific names for organisms are relatively easy to decipher because they contain their common names:

- *Amoeba amazonas*
- *Equus zebra*
- *Gekko gecko* (this lizard gets its name from the sounds it makes).
- *Gorilla gorilla*
- *Paramecium caudatum* (caudate means having a tail).

Sometimes, it is more difficult to guess their common name:

- *Apis mellifera* (honeybee, although you might have guessed this if you know that beekeeping is also called apiculture)
- *Aptenodytes patagonicus* (king penguin, although you can probably guess where it lives from its species name)
- *Loxodonta cyclotis* (African forest elephant)
- *Malus domestica* (apple tree).



The rules about writing binomial nomenclature names are that:

- **the genus name is capitalized but the species name is not**
- **both are written in italics when typed, or underlined when handwritten**
- **in addition, after these two names, often the last name of the person who first published the name in a scientific journal is given (but not italicized), and the date when it was published, for example *Equus zebra* Linnaeus, 1758.**

Scientists naming organisms sometimes have a sense of humour. Here are a few examples.

- *Albunea groeningi* Boyko, 2002. This sea snail was named after the cartoonist who created 'The Simpsons': Matt Groening.
- *Agra schwarzeneggeri* Erwin, 2002. This Costa Rican ground beetle was named after Arnold Schwarzenegger because of the insect's large biceps.
- *Dracula vampira* Luer, 1978. This orchid in Ecuador got its name from the fact that the petals on the flower look like a bat's wings.
- *Spongiforma squarepantsii* Desjardin, Peay & T.D. Bruns, 2011. This orange-coloured mushroom from Borneo gets its name from the children's cartoon character SpongeBob SquarePants.

A hierarchy of taxa

The term taxa (singular taxon) refers to the categories that scientists have generated names for. You can think of taxa as being like folders for organizing your school papers. Just as you would not (or should not) file your history notes in your maths folder, so biologists do not put birds in the same category as mammals. Likewise, within your history folder, you might have subfolders for homework, notes, tests, and so on. Within the category of plants, biologists have smaller categories for flowering plants, conifers, spore-producing plants, etc. Thus a hierarchy of taxa is used to classify species into many subcategories that are found within larger categories. There are specific names for these categories.

What do we do with viruses? How do we classify them? Viruses contain genetic information and yet they cannot reproduce outside a host cell; they do not feed, grow, or metabolize in the way that living organisms do, so they are considered to be non-living. For taxonomists, viruses are not classified as living things: they do not fall anywhere in the three domains. As a result, they are treated separately, and virologists have their own classification system.

Three domains of life

At the top of the hierarchy are the three largest groupings for organisms, called domains. The names of these three domains are the Archaea domain, the Eubacteria domain and Eukaryote domain. All living organisms are classified into one of these three. Note that viruses are not in this list because they are not alive and do not necessarily share a common ancestry with each other, two major conditions necessary to fit into this classification system (Figure 5.20 in the next section shows how the three domains are related.).

Archaeans are single-celled organisms that are distinct from bacteria and are very ancient. Archaean species thrive today in diverse habitats, from extreme conditions such as hydrothermal vents and hot springs, to the guts of mammals. Some of the beautiful colours of hot springs in places such as Yellowstone National Park are because of the presence of archaeans. The types of archaeans that prefer extreme conditions are called extremophiles and include thermophiles (heat-loving), methanophiles (methane-loving), and halophiles (salt-loving).

Grand Prismatic Thermal Springs in Yellowstone National Park. The bright colours around the edge of the hot water are caused by microbial colonies that include archaeans.

Halocins are types of antibiotics made by halophile (salt-loving) archaeans. Just as penicillin was first discovered in a fungus, lots of pharmaceutical drugs come from naturally occurring compounds. Archaeans are currently being studied for the types of organic molecules they can produce, and some of them may hold the key to fighting diseases for which we do not yet have a cure.

Eubacteria is the domain in which we find the bacteria you are most familiar with: the kind that makes your yogurt taste good, the kind that helps your intestines work properly, and also the kind that might give you an infection.

Eukaryote is the domain in which we find all other life besides Archaea and bacteria, from the microscopic single-celled yeast that helps bread to rise, to enormous organisms such as sequoia trees and blue whales. A eukaryote is recognizable by its membrane-bound nucleus and membrane-bound organelles.

Seven principal taxa

In order to classify the hundreds of thousands of different types of organisms on Earth, scientists have agreed to use a seven-level hierarchy of taxa. Each of the three domains is subdivided into these seven taxa:

- kingdom
- phylum
- class
- order
- family
- genus
- species.

The taxa that are higher up this list contain the most numbers of organisms, and the taxa at the bottom of the list contain the least number. For example, although there are hundreds of thousands of named animals in the Eukaryote kingdom (most of which are insects), there is only a single known species of humans on Earth today: *Homo sapiens*. So the higher taxa have very general characteristics encompassing many types of organisms, and the lower taxa have increasingly specific characteristics; the hierarchy narrows the categories down into smaller and smaller numbers of subcategories.

Table 5.2 shows two examples of the full identification of two species according to the seven taxa we have just named.

> **!** To help remember the order of the taxa, a mnemonic (memory trick) is helpful. Make a sentence using the first letters of each level, such as 'King Philip Came Over For Good Soup'. The human brain is very poorly adapted for remembering lists of words but very highly adapted for remembering stories. Transforming lists into stories is a good example of a mnemonic.

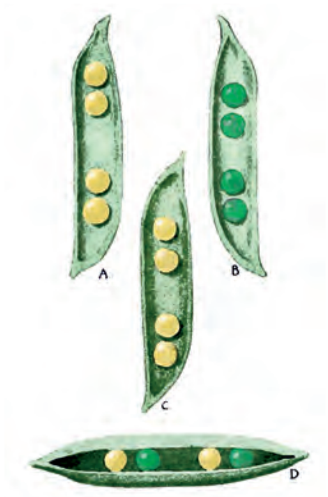


Figure 5.13 The garden pea, *Pisum sativum*, is the plant Gregor Mendel studied.

Table 5.2 The classification of two species.

Taxa	Human	Garden pea
Kingdom	Animalia	Plantae
Phylum	Chordata	Angiospermophyta
Class	Mammalia	Dicotyledoneae
Order	Primate	Rosales
Family	Hominidae	Papilionaceae
Genus	*Homo*	*Pisum*
Species	*sapiens*	*sativum*

Other classifications

The system of kingdoms and taxa is used for identifying and naming organisms, but there are countless other ways to classify organisms. Here are some examples:

- by feeding habits: carnivore/herbivore
- by habitat: land dwelling/aquatic
- by daily activity: nocturnal/diurnal
- by risk: harmless/venomous
- by anatomy: vertebrates/invertebrates

No single classification system is the 'right' way. Think of all the ways that the students in a class could be put into different groups: by eye colour, by shoe size, by birth date, by academic results, by favourite musical group, by alphabetical order, by length of fingernails, by what they had for breakfast! What is important for a system of classification is that it is clear, consistent, logical, easily implemented, and that there is a general consensus to apply it.

CHALLENGE YOURSELF

2 Look up the following things to find out what their scientific names are:

- your favourite animal
- your favourite food
- your favourite flower, tree, or house plant.

A common ancestral species

In biology, one of the objectives of classification is to represent how living (and extinct) organisms are connected. This means we are interested in natural classification, classifying organisms by their descent from a common ancestor. In Linnaeus' time, a century before Darwin and Mendel's work, the existence and function of DNA was not known, so classifications were based on observable characteristics. Today, it is preferable to use ancestry and genetics to classify organisms. The best way to establish a natural classification is to base it on DNA sequences. When the sequences are not available, the next best way is to look at derived characteristics, such as whether or not an organism can produce milk. There will be more about derived characteristics in Section 5.4.

When genetic similarities are found, a genus can be established in which all similar species are placed. The members of this genus will have all evolved from a common ancestor, and this will be evident in the similarities between their gene sequences.

Without a universal classification system, each language, culture, or region may have a different name for an organism. For example, the pill bug and woodlouse sound like two different organisms but they are, in fact, the same one: *Armadillidium vulgare*. The common names do not reveal anything about a species' evolutionary links, but its scientific name does.

You may have come across this kind of invertebrate under rotting logs.

Reclassification

As noted before, Linnaean classification was limited to observable characteristics, and in Linnaeus's time little effort was made to classify organisms by their ancestry because nothing was known about the genetic connections between species. The consequence of this is that sometimes organisms were put in the same genus even though they are not in fact closely related to each other. With a better understanding of cell structure and metabolism, as well as the new techniques of gene sequencing developed over the past few decades, we now know that some organisms that were put into the same categories in the 1700s should not be together in the same genus or even the same order.

Today, many species have been reclassified. A good example is a group of flowers called asters that were all formerly in a genus called *Aster* that comprised hundreds of species distributed widely across geographical and temperature ranges at various altitudes in Europe, Asia, and the Americas. Many species of these plants are cultivated in gardens for their decorative flowers (an example is shown in the photo on page 247). In recent decades, taxonomists have split this group into species that can trace their

ancestry to the Old World (Europe and Asia) and species that can trace their ancestry to the New World (North, Central and South America).

Looking at the ancestry of the asters, revealed in part by the structure of the single-seeded fruit they make called an achene, it was decided that there was a significant enough difference between the species on the two sides of the Atlantic Ocean that reclassification was necessary. The new classification is a better reflection of which ones are more closely related to each other. Of the genera that were put into the New World group, one example is the blue wood aster, which has now been placed in the genus *Symphyotrichum*. Table 5.3 shows what the reclassification has done to the blue wood aster's scientific name.

Table 5.3 The classification of the blue wood aster

Old classification	New classification
Aster cordifolius	*Symphyotrichum cordifolium*

Blue wood aster.

One of the challenges to renaming organisms is that books and scientific journals, as well as gardening guides and museum herbarium collections, often still have the old scientific names. This means that, before using a scientific name, it is best to check that the name respects any recent reclassifications. Fortunately, with online databases and user-generated content in web-based encyclopaedias, names can be updated and notes can be left about the previous name, so that specialists doing research can usually find a species whether or not a new or an old name has been used. One such online

How are taxonomists classified? Answer: into lumpers and splitters. In taxonomy, there are two opposing philosophies concerning what to do when an organism does not fit well into existing categories: (1) broaden the definition of an existing category to include the new organism; or (2) invent a new category or subcategory. Specialists who take the first approach are referred to as lumpers, and those who take the second approach are referred to as splitters. As you can imagine, there can be lengthy discussions between the two groups. Generally speaking, lumpers focus on the similarities between organisms, while splitters focus on the differences between organisms.

database is the Integrated Taxonomic Information System (ITIS), which you can find in the hotlinks at the end of this section.

Another challenge is that, just because a group of taxonomists decides to make a change, it does not mean that everyone will agree with that change. In addition to resistance to breaking with tradition, or the insistence of some taxonomists to maintain stability in a name no matter what, there may be some scientists who disagree with the way new groups have been determined. Just because a committee of taxonomists insists that a certain difference in cell structure is a significant enough reason to change a classification, does not mean that everyone will embrace the decision. This is one of the reasons why, long after a decision has been made, it is still possible to see an older name in field guides, databases, scientific journals, and museum labels.

Natural classification

Natural classification uses ancestry to group organisms together, whereas artificial classifications use arbitrary characteristics, such as whether or not a plant or animal tastes good, or is useful to the textile industry, or whose name begins with the letter 'c'. You may laugh, but early classification systems were often based on listing the species by alphabetical order, the way a dictionary lists words. The reasons for putting living organisms into groups according to a natural classification rather than an artificial one are numerous, and include:

- trying to make sense of the biosphere
- showing evolutionary links
- predicting characteristics shared by members of a group.

If you find a type of sea creature that you have never seen before, you should be able to find an identification key that was made by the experts who classified it. If you do a comprehensive search in the published literature of organisms that have already been identified and do not find a name for the organism, it is possible that you have discovered a new species. To put it into its appropriate category, you would find currently existing taxa that contain similar organisms. You would determine whether it had a backbone or not, if it had stinging cells or not, and so on, until you reached a family or genus that it fit into. Once you find that genus, you can look at the list of characteristics of the species in that genus and make predictions about your new species. You might be able to predict what it eats, how long it lives, whether or not it produces certain enzymes, or even certain characteristics about its cell structure or biochemistry.

In the other direction, if biologists look at characteristics common to all life forms, such as the basic information in DNA about fundamental processes such as cellular respiration and cell division, they can deduce what the common ancestor to all life was like. This organism, sometimes named LUCA for last universal common ancestor, or LUA for last universal ancestor, lived over 3.5 billion years ago and parts of its DNA code can be worked out by retracing and examining the ancestries of various forms of life.

Below, you will see some of the characteristics that scientists look for when classifying organisms. We will look at plants and animals, but be aware that there are other kingdoms not mentioned here.

Examples of plant phyla

Of the several phyla of plants, four represent many of the types of plants you are probably most familiar with.

- Bryophyta: the bryophyte phylum includes plants of very short stature, such as mosses.
- Filicinophyta: this phylum includes ferns and horsetails, among others.
- Coniferophyta: the conifer phylum includes cedar, juniper, fir, and pine trees, among others.
- Angiospermophyta: the angiosperm phylum includes all plants that make flowers and have seeds surrounded by a fruit.

Let's examine each of these phyla more closely.

Bryophyta

Bryophytes, such as the liverwort shown below, are referred to as non-vascular plants because they do not have true vascular transport tissue inside them, such as xylem tissue (which transports water and minerals up from the roots) or phloem tissue (which transports water and nutrients from the leaves towards the stem and roots).

Filicinophyta

Members of the Filicinophyta, on the other hand, are vascular plants, as are the other two phyla described in this section. Ferns are recognizable by the absence of flowers and by their triangular fronds made up of many smaller long thin leaves.

Coniferophyta

Conifers can be recognized by the fact that all of them produce woody stems and their leaves are in the form of needles or scales.

A liverwort is an example of a bryophyte.

Trees that produce seed cones and have needle-like leaves are conifers.

This mass growing on the bark of a tree branch is also a bryophyte.

Examples from different plant phyla.

The chances are that you have eaten an angiosperm today: wheat, corn, apples, and oranges are all examples of angiosperm seeds and their coverings.

Angiospermophyta

The most obvious vegetative characteristic that allows angiosperms (i.e. members of the Angiospermophyta) to be identified quickly are their flowers and fruit. If the fruit has any seeds inside, the plant is an angiosperm.

The mosses, liverworts, and hornworts that make up the bryophytes do not produce flowers or seeds. Instead, they produce spores, which are microscopic reproductive structures. Bryophyte spores are transported by rainwater and ground humidity, which is one of the reasons why they are found most abundantly in damp habitats such as a forest floor. The same is true for the plants that are filicinophytes.

In contrast, all species of conifer use wind to help them reproduce by pollination. Most species of conifer produce seed cones with seed scales.

Although angiosperms also produce seeds, they do not produce cones and they are not always pollinated by wind. Many flowering plants rely on birds, insects, and sometimes mammals to transport their pollen from one flower to the next.

The sexual reproductive organs of angiosperms are their flowers. The fruit, which is the enlarged ovary of the plant, holds the seeds.

Examples of animal phyla

Of all the phyla of animals, we will consider seven here. Some of these you may be familiar with, but others you probably do not know much about. Only one of the categories of animals in these seven phyla has a backbone or vertebral column; they are called vertebrates. The other six categories are all invertebrates: they do not have a backbone.

- Porifera: this phylum consists of the sponges.
- Cnidaria: this phylum includes sea jellies (jellyfish) and coral polyps, among others.
- Platyhelminthes: this phylum is made up of flatworms.
- Annelida: this phylum is made up of segmented worms.
- Mollusca: this phylum contains snails, clams, and octopuses, among others.
- Arthropoda: this phylum includes insects, spiders, and crustaceans, among others.
- Chordata: these are the vertebrates, the animals that have a backbone.

A yellow tube sponge, one of the members of the phylum Porifera.

Porifera

Sponges are marine animals that are sessile (i.e. they are stuck in place). They do not have mouths or digestive tracts. Rather, they feed by pumping water through their tissues to filter out food. They have no muscle or nerve tissue and no distinct internal organs.

Cnidaria

Cnidarians are a diverse group, including corals, sea anemones, jellyfish (sea jellies), hydra, and floating colonies such as the Portuguese man-of-war. This diversity makes it difficult to give an overall description of common characteristics. However, one feature that unites cnidarians is that they all have stinging cells called nematocysts.

Some of these organisms are sessile, others are free-swimming, and some can be both depending on the period of their life cycle. To digest the food they catch in their tentacles, they have a gastric pouch with only one opening. Some of the free-floating species are carried by the current, but others are agile swimmers.

Platyhelminthes

Flatworms have only one body cavity: a gut with one opening for food to enter and waste to exit. They have no heart and no lungs. One of the most famous, or infamous, members of this phylum is the parasitic tapeworm that can infest the intestines of mammals, including humans. The reason for a flatworm's flat shape is that all the cells need to be close to the surface to be able to exchange gases by diffusion. Their bodies are not segmented (divided up into sections).

The common earthworm is an annelid.

Annelida

Annelids are the segmented worms, such as earthworms, leeches, and worms called polychaetes. Here, the word segmented refers to the fact that their bodies are divided up into sections separated by rings. Annelids have bristles on their bodies, although these are not always easily visible. Like the next two phyla, annelids have a gastric tract with a mouth at one end and an opening at the other end where wastes are released.

Mollusca

Most molluscs are aquatic, and include snails, clams, and octopuses. Many produce a shell reinforced with calcium. Like annelids, they have a one-way digestive system with both a mouth and an anus. But, unlike annelids, their bodies are not segmented.

Spiders are arthropods..

Arthropoda

Arthropods have a hard exoskeleton made of chitin, segmented bodies, and limbs that can bend because they are jointed. Although the limbs are often used for walking, some are adapted for swimming, and others can form mouthparts.

Arthropods include insects, spiders, and scorpions, as well as crustaceans such as crabs and shrimps. They are true champions of diversity and adaptation because they have conquered most habitats worldwide; there are more than a million species of arthropod. They vary in size from the most minute mites, just over 100 μm long, to the Japanese giant spider crab, which is 4 m in length.

Chordata

The chordates are organisms that have a notochord at some point in their development. A notochord is a line of cartilage going down the back that provides support to the animal. It is always present at one stage in the development of a chordate organism, but can be absent from other stages. The vast majority of animals in this phylum have a bony backbone, such as birds, mammals, amphibians, reptiles, and fish, although some fish such as sharks have a cartilaginous spine instead of one made of bone. Unlike the six previous examples, these organisms are all called vertebrates. There are some exceptions to the generalization that all chordates have a backbone: sea squirts do not, for example, but are still classified in this phylum because they do develop a notochord.

When we say the word 'animal' to a child, he or she will probably think of animals with backbones, perhaps because many children's books feature vertebrates as the main characters. To a biologist, vertebrates are relatively rare; invertebrates, such as insects, are much more common on Earth.

The vertebrates

We will now explore the characteristics used to classify vertebrate organisms into the following five classes:

- fish
- amphibians
- reptiles
- birds
- mammals.

Fish

From goldfish to sharks, fish are a class of very diverse aquatic organisms that possess gills to absorb oxygen, and have skulls made of bone or cartilage. Great white sharks are well known for their jaws and teeth, and the vast majority of fish have these features, although they are not always visible. A small number of fish, such as lampreys, are jawless and use their mouths as suckers to stick onto a surface. Although fish can have limbs in the form of fins, none of the limbs have digits (fingers). Some marine mammals, such as whales, orcas, and dolphins, might resemble fish but are not, one reason being they have articulated bony fingers inside their fins.

A tadpole is the larval stage of an amphibian such as this frog. In this photo, the young frog is almost ready to leave the water because its four limbs have developed.

Amphibians

Amphibians include organisms such as frogs and salamanders; they start their lives in water. Their larval forms usually have gills to breathe underwater, but their adult forms develop lungs for breathing air. Most amphibians can also absorb oxygen through their skin. Most have four legs when they are adults, but there is a legless group called caecilians that resemble large worms or small snakes. They eat a wide variety of food, which they can chew with teeth. They might seem similar to reptiles, but their eggs do not have a membrane around the embryo. Like reptiles, however, amphibians cannot control their body temperature; they are called ectothermic (or, more informally, cold-blooded) and need to bask in the sunshine to warm up, and seek shade or water to cool off.

Reptiles

Organisms such as snakes, lizards, turtles, and alligators are classified as reptiles in part because they produce amniote eggs. Amniote eggs are characterized by having a membrane around the developing embryo to protect it, which is seen not only in reptiles with soft or hard-shelled eggs but also in birds and mammals. What sets reptiles apart from other animals is that they have scales on their body instead of feathers or fur. Like amphibians, reptiles are ectothermic; they cannot regulate their body temperature.

This marine iguana needs to bask in the sun to warm up after a cold swim in the ocean. Notice the scales covering the body, and notice the pentadactyl forelimb.

Birds

All living species of birds are bipedal (have two legs) and possess wings, most of which are adapted for flight. All birds have feathers and lay eggs with hardened shells. Bird skeletons are often very lightweight, making them well-adapted for flight. Their low density is achieved by having hollow bones. Penguins are an example of a flightless bird, but their wings are well-adapted for swimming. Birds are also characterized by the fact that their jaws are in the form of beaks with no teeth, and they usually build nests for their young, albeit in a variety of places, such as in trees, on the ground, on cliff faces, and on urban structures. Their heartbeat and breathing rates are relatively fast because they have a high rate of metabolism.

Mammals

Mammals include animals such as foxes, hippopotamuses, squirrels, and camels, and can be recognized by the fact that they have hair on their bodies and the females produce milk in specialized glands to feed their young. There are nearly 5500 species of known mammals in the world, most of which have four limbs adapted for life on land. Some mammals, such as whales and dolphins, are adapted for life in the water, and others, such as bats, are adapted for flight. Mammals are capable of thermoregulation: they maintain their body temperature at a fixed level.

Using a dichotomous key

When biologists encounter a species they do not recognize, they use a dichotomous key to establish which taxa it belongs to. If you have ever played a guessing game in which the rule is that you can only ask 'yes' or 'no' questions, then you already know how a dichotomous key works. Here are the basic principles.

1. Look at the first section of the key, which has a pair of sentences, (a) and (b), describing characteristics.
2. Next, look at the organism to see if the particular characteristic described in the first line (a) is present in the organism.
3. If the answer is yes, then go to the end of its line and find the number of the next pair of statements to look at, follow the number given and continue until the end. If the end of the line contains a name, it is the taxon for the organism.
4. If the answer is no, then go to the second statement just below it (b) and that one should be true, so go to the end of its line and find the number of the next pair of statements to look at. Follow the number given and continue until the end.

Keep going until you get to a name instead of a number: if you have answered each question correctly, that will be the name of the taxon your organism belongs to. Try identifying the organisms shown opposite using the key in the following example.

Worked example

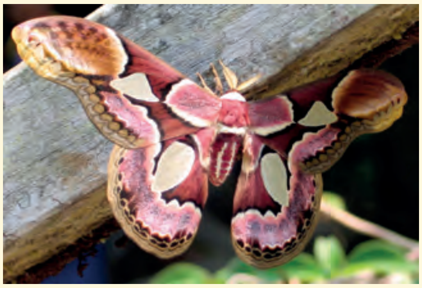
Here is an example of a key for identifying the animal taxa listed in this chapter.

1	(a) No differentiated tissues, no symmetry or identifiable organs..	Porifera
	(b) Presence of differentiated tissues and organs..............................	2
2	(a) Stinging cells present, can show radial symmetry.......................	Cnidaria
	(b) No stinging cells..	3
3	(a) Has two-way digestive tract and bilateral symmetry	Platyhelminthes
	(b) Has a one-way digestive tract (mouth and anus).........................	4
4	(a) Does not possess a notochord at any time...................................	5
	(b) Possesses a notochord at some stage..	7
5	(a) Has an exoskeleton made of chitin	Arthropoda
	(b) Does not have an exoskeleton made of chitin..............................	6
6	(a) Has a segmented body	Annelida
	(b) Makes a shell reinforced with calcium...	Mollusca
7	(a) Four limbs present, with articulated digits...................................	8
	(b) Limbs present, but they do not have digits	Fish

8 (a) Does not produce an amnion .... Amphibians
(b) Can produce an amnion 9
9 (a) Presence of hair on the body, can make milk to feed young ...... Mammal
(b) Absence of hair, cannot make milk 10
10 (a) Body covered with feathers .... Bird
(b) Body covered with scales .... Reptile

Use the key to find out which taxon each organism pictured below is in. Show how you did your work by writing the numbers and letters you followed.

1



2

3

4

Solutions

1. 1b →2b →3b →4a →5a = Arthropoda
2. 1b →2a = Cnidaria
3. 1b →2b →3b →4b →7a →8b →9b →10b = Reptile
4. 1b →2b →3b →4a →5b →6b = Mollusca

CHALLENGE YOURSELF

3 Construct your own dichotomous key for use in identifying specimens. Because the example shown is for animal taxa in this chapter, try one for the plant taxa described in this chapter.

Campers and hikers can use a dichotomous key in a field guide to be sure that any mushrooms or plants they find are edible and not poisonous. They can also use a key to determine whether or not certain plants are endangered or protected species.

TOK

In his classification of organisms, Linnaeus used physical characteristics and social behaviour to establish four groups of humans. Reading such descriptions today is shocking because, by modern standards, they have a racist nature. To what extent is it necessary to consider the social context of scientific work when evaluating ethical questions about research?

To learn more about taxonomy and classification, go to the hotlinks site, search for the title or ISBN, and click on Chapter 5: Section 5.3.

Exercises

9 List the three classification domains. Determine which domain each of the following organisms belongs to.
- **(a)** A single-celled organism that prefers very salty water.
- **(b)** Algae (hint: they have a nucleus).
- **(c)** Spider.
- **(d)** *Escherichia coli*.

10 Suggest one reason why viruses do not fit into the three-domain system.

11 Make a table with four columns headed Bryophyta, Filicinophyta, Coniferophyta, and Angiospermophyta. Make two rows labelled 'Physical characteristics' and 'Named examples'. Complete the eight empty cells of the table.

12 In the seven-taxa system, state the order that you belong to.

13 Using 10 different objects found in your school bag, design a dichotomous key.

NATURE OF SCIENCE

Falsification of theories with one theory being superseded by another: plant families have been reclassified as a result of evidence from cladistics.

5.4 Cladistics

Understandings:

- A clade is a group of organisms that have evolved from a common ancestor.
- Evidence for which species are part of a clade can be obtained from the base sequences of a gene or the corresponding amino acid sequence of a protein.
- Sequence differences accumulate gradually so there is a positive correlation between the number of differences between two species and the time since they diverged from a common ancestor.
- Traits can be analogous or homologous.
- Cladograms are tree diagrams that show the most probable sequence of divergence in clades.
- Evidence from cladistics has shown that classifications of some groups based on structure did not correspond with the evolutionary origins of a group or species.

Applications and skills:

- Applications: Cladograms including humans and other primates.
- Application: Reclassification of the figwort family using evidence from cladistics.
- Skill: Analysis of cladograms to deduce evolutionary relationships.

Characteristics used for classification

Table 5.4 shows some types of characteristics that botanists and zoologists might study in order to help them decide how to classify an organism.

Table 5.4 Types of characteristics used for classifying organisms

Characteristic	Example/reason
Morphology	The shape of a plant's seed coat or the shape of a bird's bill
Anatomy	The number of petals on a flower or the type of digestive system in an invertebrate
Cytology	The structure of cells or their function
Phytochemistry	Special organic compounds that only plants can make, often to protect themselves from attack by insects
Chromosome number	Two species with the same chromosome number are more likely to be closely related than those with differing numbers
Molecular differences	Proteins and DNA sequences differ between one species and another

Classifying organisms using molecular differences is called molecular systematics. As technology is improved and becomes more affordable, more and more specialists are using methods involving protein sequences and DNA.

Clades

Cladistics is a system of classification that groups taxa together according to the characteristics that have evolved most recently. In this system, the concept of common descent is crucial to deciding into which groups to classify organisms. Cladistics is, therefore, an example of natural classification. To decide how close a common ancestor is, researchers look at how many primitive and derived traits the organisms share.

Primitive traits (also called plesiomorphic traits) are characteristics that have the same structure and function (e.g. leaves, with vascular tissue to transport liquids around a plant) and that evolved early on in the history of the organisms being studied. Derived traits (also called apomorphic traits) are also characteristics that have the same structure and function but that have evolved more recently as modifications of a previous trait (e.g. flowers, which evolved more recently than leaves with vascular tissue, i.e. they are an adaption of vascular leaves). By systematically comparing such characteristics, quantitative results show which organisms have a more recent split in the evolutionary past and which have a more distant split.

When a group can be split into two parts, one having certain derived traits that the other does not have, the groups form two separate clades. A clade is a monophyletic group. This means it is a group composed of the most recent common ancestor of the group and all its descendants. Although a clade can sometimes have just one species, usually it is made up of multiple species.

Biochemical evidence of clades

Biochemical evidence, including DNA and protein structures, has brought new validity and confirmation to the idea of a common ancestor. For example, the fact that every known living organism on Earth uses DNA as its main source of genetic information is compelling evidence that all life on Earth has a common ancestor. As you saw in Section 3.5 on genetic engineering, any gene from any organism can be mixed and matched with DNA from other organisms to generate a certain protein. Other than conceding that we all have a common ancestor, it would be difficult to explain how else this is true.

In addition, all the proteins found in living organisms use the same 20 amino acids to form their polypeptide chains. Again, this has been confirmed by the introduction of foreign genes using genetic engineering to get an organism to synthesize a protein that it never synthesized before.

Amino acids can have two possible orientations: left-handed and right-handed, depending on the way their atoms are attached together. The overwhelming majority of living organisms on Earth use left-handed amino acids to build their proteins, and only a small number of organisms (notably some bacteria) can use right-handed amino acids. For those who support the idea of the biochemical evolution of life, the most logical explanation for such chemical similarities is that they imply a common ancestry for all life forms that use left-handed amino acids to build their proteins.

Variations and phylogeny

Phylogeny is the study of the evolutionary past of a species. Species that are the most similar are most likely to be closely related, whereas those that show a higher degree of differences are considered less likely to be closely related. By comparing the similarities in the polypeptide sequences of certain proteins in different groups of animals, it is possible to trace their common ancestry. This has been done with the blood protein haemoglobin, with a mitochondrial protein called cytochrome *c*, and with chlorophyll, to name just three proteins.

With advances in DNA sequencing, the study of nucleic acid sequences in an organism's DNA, as well as its mitochondrial DNA, has been effective in establishing biochemical phylogeny. Changes in the DNA sequences of genes from one generation

to the next are partly due to mutations, and the more differences there are between two species, the less closely related the species are.

Here is an imaginary example of a DNA sequence from four different organisms:

1 A A A A T T T T C C C C G G G G
2 A A A A T T T A C C C C G G G G
3 A A A A T T T A C C C G C G G G
4 A A C A T C T A C C A G C C T G

The differences have been highlighted in red. It should be clear that species 1 and 2 have the fewest differences between them, whereas species 1 and 4 have the most differences. As we have seen in Chapter 4, these differences can arise as a result of mutations. The second sequence shows only one difference with the first, but the fourth shows eight differences. The conclusion could be that species 1 and 2 are more closely related to each other than they are to species 3 or 4.

Figure 5.14 A representation of the relationships between four species

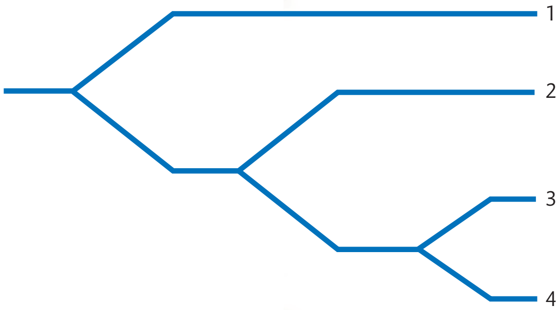


Figure 5.14 shows how these four imaginary species could be related:

Often, such work by biochemists confirms what palaeontologists have hypothesized about the ancestries of the fossils they have studied. When one branch of science confirms the work of another branch, the findings have more credibility. In other cases, the biochemical evidence can be contradictory, which encourages scientists to reconsider their initial ideas.

The evolutionary clock

Differences in polypeptide sequences accumulate steadily and gradually over time, as mutations occur from generation to generation in a species. Consequently, the changes can be used as a kind of clock to estimate how far back in time two related species split from a common ancestor.

By comparing homologous molecules from two related species, it is possible to count the number of places along the molecules where there are differences. If the molecule is mitochondrial DNA, for example, we count the number of base pairs that do not match. Mitochondrial DNA is particularly interesting to study because, unlike DNA found in the cell's nucleus, it is not shuffled and mixed during meiosis or fertilization: it is passed on directly from mother to child without modification. This is why we can be sure that any modifications in mitochondrial DNA are due solely to mutations.

Imagine comparing certain DNA sequences from three species, A, B, and C. Between the DNA samples from species A and species C there are 83 differences. Between species A and species B there are only 26 differences. From these data, we can conclude that species B is more closely related to species A than species C is. There has been more time for DNA mutations to occur since the split between A and C than since the split between A and B.

One technique that has been successful in measuring such differences is DNA hybridization. The idea is simple: take one strand of DNA from species A and a homologous strand from species B and fuse them together. Where the base pairs connect, there is a match; where they are repelled and do not connect, there is a difference in the DNA sequence and therefore there is no match (see Figure 5.15).

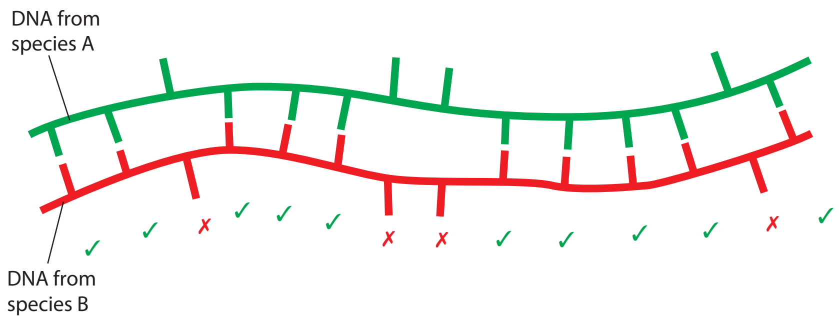


Figure 5.15 DNA hybridization between a strand of DNA from one species (in green) and another from a second species (in red). There are four places where a match does not occur.

We can take this further. If we see that 83 nucleotide differences is approximately three times more than 26 differences, we can hypothesize that the split between species A and species C happened about three times further back in the past than the split between the species A and B. This is the idea of using quantitative biochemical data as an evolutionary clock to estimate the time of the speciation events (see Figure 5.16).

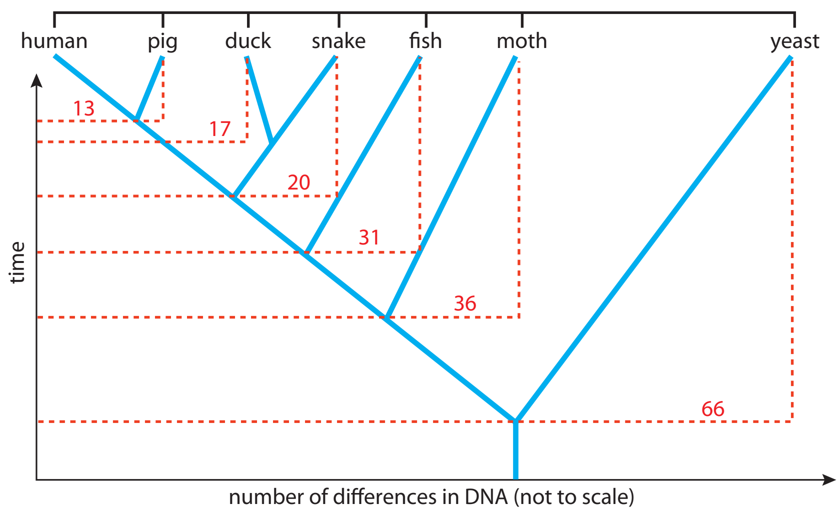


Figure 5.16 Biochemical differences (dotted red lines) can be used to see how far apart species are on a phylogenetic tree (in blue).

However, we need to be careful when using a word such as 'clock' in this context. Under no circumstances should we consider that the 'tick-tock' of the evolutionary clock, which is made up of mutations, is as constant as the ticking of a clock on the wall. Mutations can happen at varying rates. Consequently, all we have is an average, an estimation or a proportion, rather than an absolute time or date for speciation events. In an effort to double-check the timing of the evolutionary clock, biochemical data can be compared with morphological fossil evidence and radioisotope dating.

Experts in various fields of study use this idea of accumulated change over time. For example, linguists look at changes in words and uses of vocabulary to trace the evolution of a language throughout the course of history. Some language experts can deduce when pigs were domesticated in a particular country just by looking at the names for 'pig' in the various languages in and around that country. Experts who study chain letters sent by the post or by email are interested in the number of modifications to the original letter over time. By comparing hundreds of versions of the same message, they can analyse what has been added or changed to see its evolution over time. With enough evidence, it is sometimes possible to deduce the origin and approximate date of the original letter in a chain, even if that letter was never found.

Analogous and homologous traits

In examining the traits of organisms in order to put them into their appropriate clades, thorough and systematic studies of their characteristics must be undertaken. Two types of characteristic that are considered are homologous characteristics and analogous characteristics.

As we saw earlier in this chapter, homologous characteristics are ones derived from the same part of a common ancestor. The five-fingered limbs found in such diverse animals as humans, whales, and bats are examples of homologous anatomical structures. The shape and number of the bones may vary, and the function may vary, but the general format is the same, and the conclusion is that the organisms that possess these limbs had a common ancestor.

What do the sarcastic fringehead fish and the bald eagle have in common? Eyes: a homologous characteristic.

Another example of a homologous characteristic is the presence of eyes. Such structures are seen in both vertebrates and invertebrates. Simple eyes found in molluscs such as the *Nautilus* function as pinhole cameras without a system of lenses, whereas highly evolved eyes like those of birds of prey use crystalline lenses, adjustable irises, and muscles to help focus on objects at different distances. Yet both types of eye have evolved from a common ancestor, because they all use one form or another of pigment cells and specialized nerve cells called photoreceptors that are light sensitive (see Chapter 12, Section A.3).

Homology is observed in DNA sequences as well. Certain combinations of base pairs coding for similar proteins can be found in diverse organisms. As with homologous anatomical features, these sequences are evidence of a common ancestry. The cytochrome *c* sequence studied in Section 3.1 is one example.

In contrast, analogous characteristics are those that may have the same function but they do not necessarily have the same structure and they are not derived from a common ancestor. Wings used for flying are an example: eagles, mosquitoes, bats, and extinct reptiles such as the pterosaurs all use (or used) wings to fly. Although these organisms are all classified in the animal kingdom, they are certainly not placed in the same clade simply because of their ability to fly with wings. There are many other characteristics that must be considered.

Another example of an analogous characteristic is fins in aquatic organisms. Both sharks and dolphins have pectoral fins that serve a very similar function: helping them to swim well. But sharks are fish whereas dolphins are aquatic mammals, and the two are classified differently in both the Linnaean system and in cladistics.

To help you remember the difference between analogous and homologous, remember that these terms refer to anatomy (the flesh and blood) and that an analogy is used to compare very different things. The term 'homo' means same, so homologous refers to anatomically similar things.

Cladograms

To represent the findings of cladistics in a visual way, a diagram called a cladogram is used. A cladogram showing bats, sharks, and dolphins, for example, would take into account their skeletal structures and other characteristics, such as the fact that bats and dolphins are mammals (see Figure 5.17). Thus, bats and dolphins are shown as more similar to each other than sharks are to either.

Figure 5.17 shows some key characteristics of a cladogram. For example, a node is the place where a speciation happened and where the common ancestor was found. The clade shown in yellowy green is divided up into a sister group, a group showing the closest relatives, and an outgroup, which is a group that is less closely related to the others in the cladogram. Sharks are less closely related to bats and dolphins than bats and dolphins to each other. And yet, if we go back far enough, we will find another node showing that they do eventually have a common ancestor.

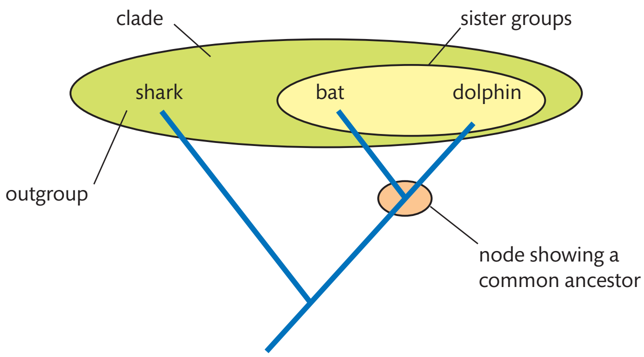


Figure 5.17 A cladogram showing three taxa organized into a clade, of which two are sister groups and one is an outgroup. Nodes show a common ancestor for the descendants that appear above them in this cladogram.

Worked example

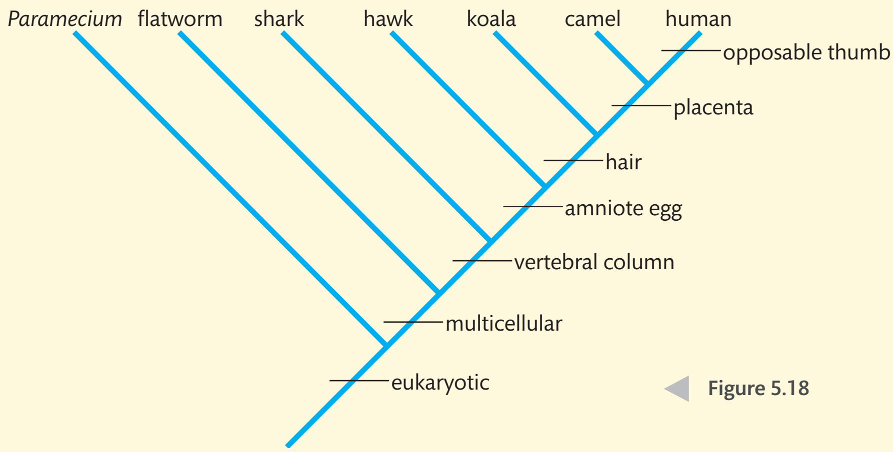


Figure 5.18

1 What is the primitive characteristic in the cladogram shown in Figure 5.18?
2 Name the members of the mammal clade in this cladogram.
3 What is the outgroup when considering the clade of multicellular organisms?
4 Do shark eggs have a protective membrane (the amnios) around them?
5 Explain why there are no bacteria shown in this diagram.

Solutions

1 Being eukaryotic is the primitive characteristic shared by all.
2 Koala, camel, human.
3 The *Paramecium*.
4 No. Sharks are not amniotes.
5 Because the primitive characteristic requires the organisms to have a nucleus. If bacteria were to be added to this cladogram, a new primitive characteristic would need to be chosen.

The essential idea behind cladograms constructed by studying biochemical differences is that an organism with the fewest modifications of a particular DNA sequence will be the most anciently evolved, and those with the most modifications (mutations) in the same DNA sequence will be the more recently evolved organisms. The former have nodes at the earliest splits of the cladogram, and the latter have nodes at the more recent splits.

Cladograms and classification

Cladistics attempts to find the most logical and most natural connections between organisms in order to reveal their evolutionary past. Cladistics is the study of clades, and cladograms are the diagrams that show the phylogeny of the clades being studied.

Every cladogram drawn is a working hypothesis. It is open for testing and for falsification. On the one hand, this makes cladistics scientific, but on the other hand, if it is going to be changing in the future as new evidence arises, it could be criticized for its lack of integrity.

Each time a derived characteristic is added to the list shared by organisms in a clade, the effect is similar to going up one level in the traditional hierarchy of the Linnaean classification scheme. For example, the presence of hair is part of what defines a mammal, so any species found after the line marked 'hair' should be in the class of mammals.

What about feathers? If an organism has feathers, is it automatically a bird? In traditional Linnaean classification, birds occupy a class of their own, but this is where cladistics comes up with a surprise. When preparing a cladogram, it becomes clear that birds share a significant number of derived characteristics with a group of dinosaurs called the theropods. This suggests that birds are an offshoot of dinosaurs rather than a separate class of their own.

Because birds are one of the most cherished and well-documented classes of organisms on Earth, this idea, when it was first suggested, was controversial to say the least. Some of the derived characteristics used to put birds and dinosaurs in the same clade are:

- a fused clavicle (the 'wishbone')
- flexible wrists
- hollow bones
- a characteristic egg shell
- the hip and leg structure, notably with backward-pointing knees.

By following the idea of parsimony, it is more likely that birds evolved from dinosaurs than from another common ancestor. This is where cladistics is clearer than the Linnaean system. In cladistics, the rules are always the same concerning shared derived characteristics and parsimony. In the Linnaean system, apart from the definition of species, which we have already seen is sometimes challenged, the other hierarchical groupings are not always clearly defined: what makes a class a class, or a phylum a phylum? Centuries after Linnaeus, we are still debating this question today.

Reclassification

From time to time, new evidence about a taxon requires a new classification. Either the taxon can be moved up or down the hierarchy (family to subfamily, for example), or from one family to another.

Plants commonly known as figworts used to be classified in the family Scrophulariaceae, and many of them have been used in herbal medicine. The name Scrophulariaceae, sometimes affectionately referred to by botanists as 'scrophs', comes from the time when plants were frequently named for the diseases they could be used

to treat. The medical term 'scrofula' refers to an infection of the lymph nodes in the neck. Preparations made with figwort were given to patients who suffered from this infection, which was associated with tuberculosis.

The common foxglove, *Digitalis purpurea*, has been reclassified, so instead of being in the figwort family it is now in the plantain family.

Before the mid-1990s, the family Scrophulariaceae was characterized by morphological features such as how the flower petals were arranged in the bud before the flower opens. This feature is called aestivation, and botanists look for whether the flower petals overlap with each other or whether they are arranged in a spiral or not. Another characteristic that was used was the morphology of the nectaries, the parts of the flower that make nectar.

Since the mid 1990s, DNA analysis of the plants classified in this taxon have led botanists to rethink their classification. Analysis of zones of DNA markers such as the nuclear ribosomal internal transcribed spacer (ITS) region has revealed that the old classification system was not monophyletic, meaning the taxa did not share a most recent common ancestor. Rather, the old system was grouping together plants that belonged to separate branches, making it impossible to fit them into a cladogram.

The term used to describe species on separate branches is paraphyletic, so we now know that the old family Scrophulariaceae was paraphyletic. As an analogy, it would be similar to someone meeting your extended family for the first time and incorrectly assuming that your second cousins were your brothers and sisters, simply because you all had similar physical features. DNA testing would clearly show that second cousins have a more distant common ancestor than siblings do.

Plants that were in the Scrophulariaceae family have been given new families to belong to. One of the families that has incorporated species from the old classification is the family Plataginaceae, and that is where we now find foxgloves. Foxgloves are now classified in a way that shows that they are more closely related to plantains; they are no longer considered to be figworts.

Moving the branches of the tree of life around and reclassifying a taxon in a new branch in this manner means changing the species' circumscription. Circumscription is the process of placing taxa where they clearly show monophyletic groups, allowing us to show that they all share a recent common ancestor.

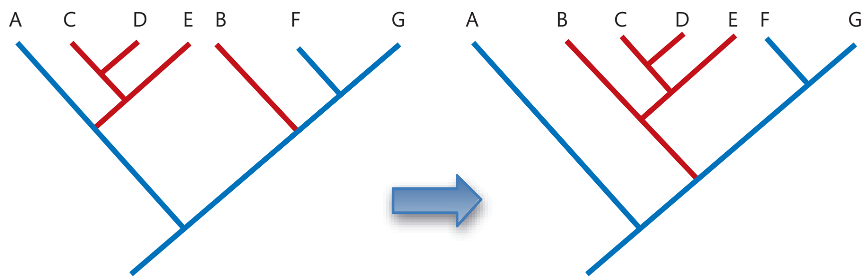


Figure 5.19 An example of a modification of a species' circumscription. The clade that included species C, D, and E on the left was moved from the branch that included species A, and placed on the branch with species B instead, because C, D, and E show a common ancestry with species B. In the old cladogram on the left, B, C, D, and E are shown as being paraphyletic, whereas the new cladogram on the right is showing them as monophyletic.

TOK

Every once in a while a new idea comes along and shakes the scientific community to the core. Reclassifying thousands of organisms by creating a new category of taxon would be a good example, and that is precisely what Carl Woese did in 1977. He proposed the domain Archaea.

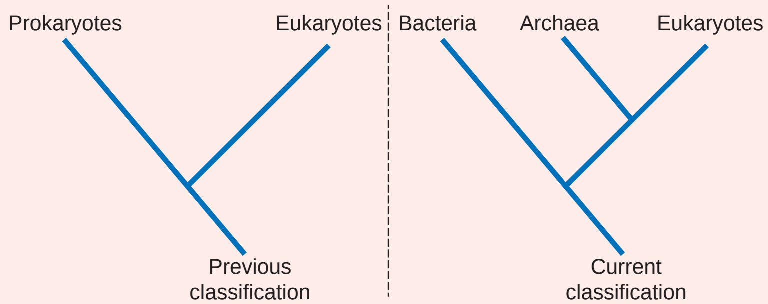


Figure 5.20 The classification of Archaea.

Influential scientists at the time, including Nobel laureate Salvador Lurid and eminent evolutionary biologist Ernst Mayr, opposed splitting the prokaryotes in this way. This is an illustration of how some scientists are conservative and prefer to keep things the way they are. What benefits does conservatism have in science?

NATURE OF SCIENCE

Notice how the reclassification of the foxglove is a good example of how scientists work. Observations were made initially based on morphology. The plant was classified into specific categories that included the family Scrophulariaceae, the figwort family. DNA sequencing was done on many species including foxgloves, and it was determined that some plants did not belong with the other figworts but instead belonged in the family Plantaginaceae along with the plantains. Studies were published in recognized botany journals and now foxgloves have a new family.

A certain amount of communication is needed in order to get everyone to use the new classification. Books on botany and websites on plant conservation, as well as university courses and online databases, must be updated, and the best ones make sure they are backwards compatible (making reference to the previous classification) and forwards compatible (incorporating the latest classification). Not everyone was happy about putting foxgloves with plantains, because visually the plants do not appear to have much in common. But nature is often counterintuitive. If things were obvious in nature, we wouldn't need science to understand it.

Worked example

1 Examine this cladogram of four genera of plants.
   (a) Name two sister taxa.
   (b) Name the outgroup in this cladogram.
   (c) Using a clearly marked label, indicate a node.
   (d) Which genus possesses characteristics that evolved more recently, *Digitalis* or *Plantago*?

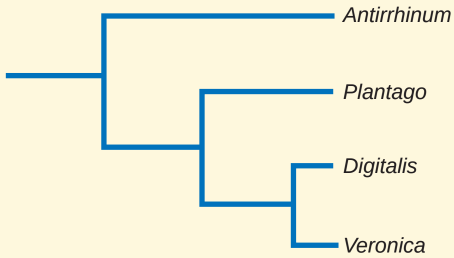


Figure 5.21

2 Study the phylogenic tree below showing some primates and their chromosome numbers. Note that when there is great variety between one species and another within a taxon, a range of chromosome numbers is given.
   (a) Identify the numbered arrow that indicates a common ancestor for all the primates shown.
   (b) Monkeys have tails whereas apes do not. Arrow number 3 shows the point when primates lost their tails. List the apes shown in the diagram.
   (c) Identify the numbered arrow that indicates when bipedalism completely replaced walking on four legs.
   (d) The great apes are the four primates shown that demonstrate the most recently developed derived traits. Identify which taxon in the diagram represent the lesser apes.
   (e) All the great apes shown except one has the same number of chromosomes? Which species has a different number?
   (f) Some evidence supports the idea that, in humans, two of our chromosomes fused together at some point in our evolution. What evidence is there in the cladogram to support this?

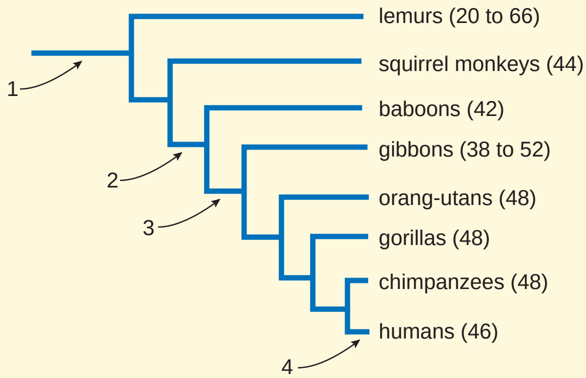


Figure 5.22

Solutions

1 (a) *Digitalis* and *Veronica*.
   (b) *Antirrhinum*.
   (c) Answers may vary: anywhere a horizontal line comes to a 'T' with a vertical line.
   (d) *Digitalis* (it is the product of a more recent speciation).

2 (a) 1.
   (b) Gibbons, orang-utans, gorillas, chimpanzees, humans.
   (c) 4.
   (d) Gibbons.
   (e) Humans.
   (f) All of our closest relatives in the great apes clade have 48 chromosomes whereas we have 46; this would suggest that, if one pair of chromosomes fused with another, we would have gone from 24 pairs to 23 pairs.

Exercises

14 Distinguish between analogous and homologous structures.

15 Observe the three amino acid sequences below showing amino acids 100 to 116 in one of the polypeptides that makes up haemoglobin. Next to the human's sequence are two other species, A and B.

Amino acid	Human	Species A	Species B
100	PRO	PRO	PRO
101	GLU	GLU	GLU
102	ASN	ASN	ASN
103	PHE	PHE	PHE
104	ARG	LYS	ARG
105	LEU	LEU	LEU
106	LEU	LEU	LEU
107	GLY	GLY	GLY
108	ASN	ASN	ASN
109	VAL	VAL	VAL
110	LEU	LEU	LEU
111	VAL	VAL	ALA
112	CYS	CYS	LEU
113	VAL	VAL	VAL
114	LEU	LEU	VAL
115	ALA	ALA	ALA
116	HIS	HIS	ARG

(a) How many differences are there between the human sequence and the sequence of species A?

(b) How many differences are there between the human sequence and the sequence of species B?

(c) One of the sequences belongs to a horse and the other to a chimpanzee: which is species B more likely to be? Justify your answer.

Practice questions

1 Which of the following are used as evidence for evolution?

I. Homologous structures.

II. Selective breeding of domesticated animals.

III. Overproduction of offspring.

A I and II only.

B I and III only.

C II and III only.

D I, II and III. *(Total 1 mark)*

2 Outline the process of adaptive radiation. *(Total 3 marks)*

3 What is the mechanism of natural selection?

A Any individuals in a population can be selected entirely by chance.

B After a change in the environment a species will evolve adaptations to the new conditions.

C If an adaptation to the environment is useful, an individual will develop it and pass it on to its offspring.

D Variations amongst individuals of a population are selected by a changing environment.

(Total 1 mark)

4 Antibiotic resistance in bacteria is an example of evolution in response to environmental change. Using another example, explain how an environmental change can lead to evolution.

(*Total 8 marks*)

5 What are *Allium sativa* and *Allium cepa*?

A Two different species of the same genus.

B The same species of the same genus.

C The same species but of a different genus.

D Two different species of a different genus. (*Total 1 mark*)

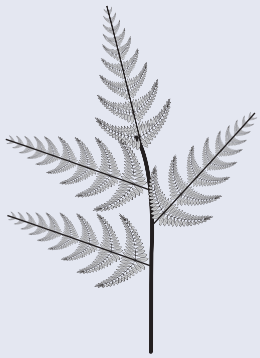
6 Which phylum does the plant below belong to?

A Angiospermophyta.

B Bryophyta.

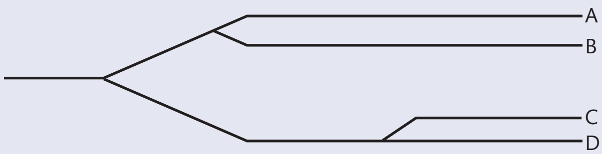
C Coniferophyta.

D Filicinophyta.



(*Total 1 mark*)

7 The cladogram below shows the classification of species A to D. Deduce how similar species A is to species B, C, and D.



(*Total 2 marks*)

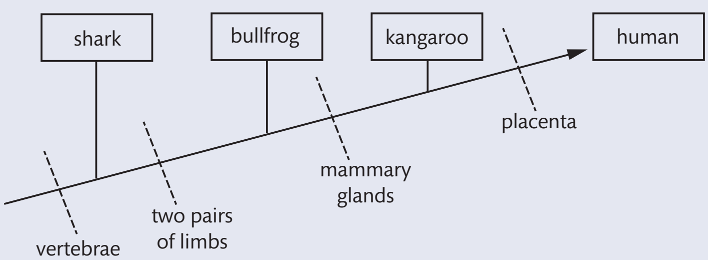
8 Using examples, distinguish between analogous characteristics and homologous characteristics.

(*Total 4 marks*)

9 Suggest two reasons for using cladograms for the classification of organisms.

(*Total 2 marks*)

10 Analyse the relationship between the organisms in the following cladogram.



(*Total 3 marks*)